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DEVELOPMENT OF A NITROGEN GENERATION SYSTEM

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FINAL REPORT

by

D. B. Heppner, R. D. Marshall,
J. D. Powell, III and F. H. Schubert

January, 1980

Prepared Under Contract NAS2-10096

by

Life Systems, Inc.
Cleveland, OH 44122

for

AMES RESEARCH CENTER
National Aeronautics and Space Administration

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. during the period December, 1978 to January, 1980. The Program Manager was Richard D. Marshall. Support was provided as follows:

Personnel	Area(s) of Responsibility
Steve Czernec	Mechanical Hardware Assembly and Checkout
Tim M. Hallick	NSS Testing and Data Reduction
Dennis B. Heppner, Ph.D.	NSS/ARX-1 Integration and Testing
Ronald H. Kohler	Contract Administration
Jim D. Powell, III	Control/Monitor Instrumentation Checkout
Franz H. Schubert	System Design Support
Pat Y. Yang, Ph.D.	Control Software Design

The contract's Technical Monitor was P. D. Quattrone, Chief, Advanced Life Support Office, NASA Ames Research Center, Moffett Field, CA.

TABLE OF CONTENTS

continued-

Table of Contents - continued

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ARS	Air Revitalization System
ARX-1	One-Person, Experimental Air Revitalization System
CHCS	Cabin Humidity Control Subsystem
C/M I	Control/Monitor Instrumentation
CRS	CO_2 Reduction Subsystem
EC/LSS	Environmental Control/Life Support Subsystem
EDC	Electrochemical Depolarized CO_2 Concentrator
NGM	Nitrogen Generation Module
NGS	Nitrogen Generation System
NSS	Nitrogen Supply Subsystem
OGS	Oxygen Generation Subsystem
S-CRS	Sabatier-Based CO_2 Reduction Subsystem
TSA	Test Support Accessories
WHS	Water Handling Subsystem

SUMMARY

A research and development program was successfully completed at Life Systems, Inc. towards the development of a method of generating nitrogen for cabin leakage makeup aboard space vehicles. This nitrogen generation concept uses liquid hydrazine as the stored form of nitrogen to reduce tankage and expendables weight associated with high pressure gaseous or cryogenic liquid nitrogen storage. The hydrazine is catalytically dissociated to yield a mixture of hydrogen and nitrogen. The latter is separated to provide the makeup nitrogen. The byproduct hydrogen is used in the reduction of metabolic carbon dioxide.

The development of an eight-stage Nitrogen Generation Module has been completed. The design successfully integrates a hydrazine catalytic dissociator, three ammonia dissociation stages and four palladium/silver hydrogen separator stages. Alternating ammonia dissociation and hydrogen separation stages are used to remove hydrogen and ammonia formed in the dissociation of hydrazine which results in negligible ammonia and hydrogen concentrations in the product nitrogen stream. The high-purity nitrogen contains less than or equal to 0.2% hydrogen and 50 parts per million ammonia. The dissociation and separation stages are packaged as a single unit to minimize heat rejection to ambient since both operate at elevated temperatures. The single package concept allows the heat generated during the dissociation of hydrazine to reduce the heater power required to maintain the Nitrogen Generation Module at temperature.

The development of an engineering breadboard Nitrogen Supply Subsystem as an integratable subsystem for a central spacecraft Air Revitalization System has been completed. The subsystem consists of the hydrazine storage and feed mechanism, the Nitrogen Generation Module, the peripheral mechanical and electrical components required to control and monitor subsystem performance and the instrumentation required to interface with other subsystems of an Air Revitalization System. The Nitrogen Supply Subsystem has been designed to deliver nitrogen at a rate of 3.6 kg/d (8.0 lb/d) at pressures of 1725 kPa (250 psia) or less. The subsystem recovers 84% (with the remaining vented to vacuum) of the hydrogen contained in the feed hydrazine stream and delivers 0.44 kg/d (0.96 lb/d) of hydrogen for use in the reduction of carbon dioxide.

The breadboard Nitrogen Supply Subsystem has been integrated with a one-person capacity experimental Air Revitalization System. The latter provided a test bed to test and evaluate the operation of the Nitrogen Supply Subsystem. The integration, checkout and testing was successfully accomplished. The program activities showed that hardware can be developed to meet future central Air Revitalization System requirements. Future activities are required to experimentally characterize the hardware developed and establish the performance level and data base for flight hardware designs. The data gathered will also reflect the subsystem's maturity level for flight application. In addition, development of a self-contained Nitrogen Supply Subsystem is recommended.

INTRODUCTION

Future long-term manned spacecraft missions will utilize an atmosphere of nitrogen (N_2) and oxygen (O_2). Space vehicle gas leakage and cabin repressurization requirements following extravehicular missions necessitate on-board

storage of the primary cabin atmospheric constituents, N_2 and O_2. The N_2 component of air can be stored as liquid hydrazine (N_2H_4) and the N_2H_4 catalytically dissociated to an N_2 and hydrogen (H_2) mixture.[2] The N_2/H_2 mixture is then separated to yield the makeup N_2. The byproduct H_2 is used in the reduction of metabolically-generated carbon dioxide (CO_2). The advantage of supplying N_2 through N_2H_4 compared to gaseous or cryogenic storage is shown in Figure 1.

A research and development program has been established to evolve the capability for generating N_2 for cabin leakage makeup aboard a space vehicle of mission durations requiring regenerative methods for reprocessing the crew's metabolic products. The development program is focused on the Nitrogen Supply Subsystem (NSS) for a regenerative Environmental Control/Life Support Subsystem (EC/LSS).

Background

During an earlier program[1] Life Systems, Inc. (LSI) identified two attractive N_2 generation systems based on the catalytic dissociation of N_2H_4. In the first system, liquid N_2H_4 is catalytically dissociated to yield an N_2/H_2 gas mixture. Separation of the gas mixture to yield N_2 and byproduct H_2 is accomplished using a Polymer-Electrochemical N_2/H_2 Separator.[2,3] In the second system, the N_2/H_2 product gas from the dissociator is separated in a palladium/silver (Pd/Ag) N_2/H_2 Separator.

The program culminated in the successful design, fabrication and testing of an N_2H_4 Catalytic Dissociator, a Polymer Electrochemical N_2/H_2 Separator and a two-stage Pd/Ag N_2/H_2 Separator. Based on the results of this program it was recommended that an N_2 Generation System (NGS), and subsequently an NSS, be developed based on N_2H_4 catalytic dissociation and the Pd/Ag method of H_2 separation.

During a following program,[4,5] LSI developed and tested various components of the NSS including an NGM, N_2H_4 storage and advanced instrumentation. Tests were conducted to support the development of the NGM and advance NSS technology. The current program continued the NSS development by implementing and testing an engineering breadboard NSS.

Program Objectives

The objectives of the program were to develop and evaluate:

1. A Nitrogen Generation Module (NGM) incorporating advances in sealing techniques,

2. An engineering breadboard of the NSS which incorporates the NGM and is integrated within a one-person, experimental Air Revitalization System (ARX-1), and

3. The integration concepts through actual operation of an NSS.

(1) References cited are at the end of this report.

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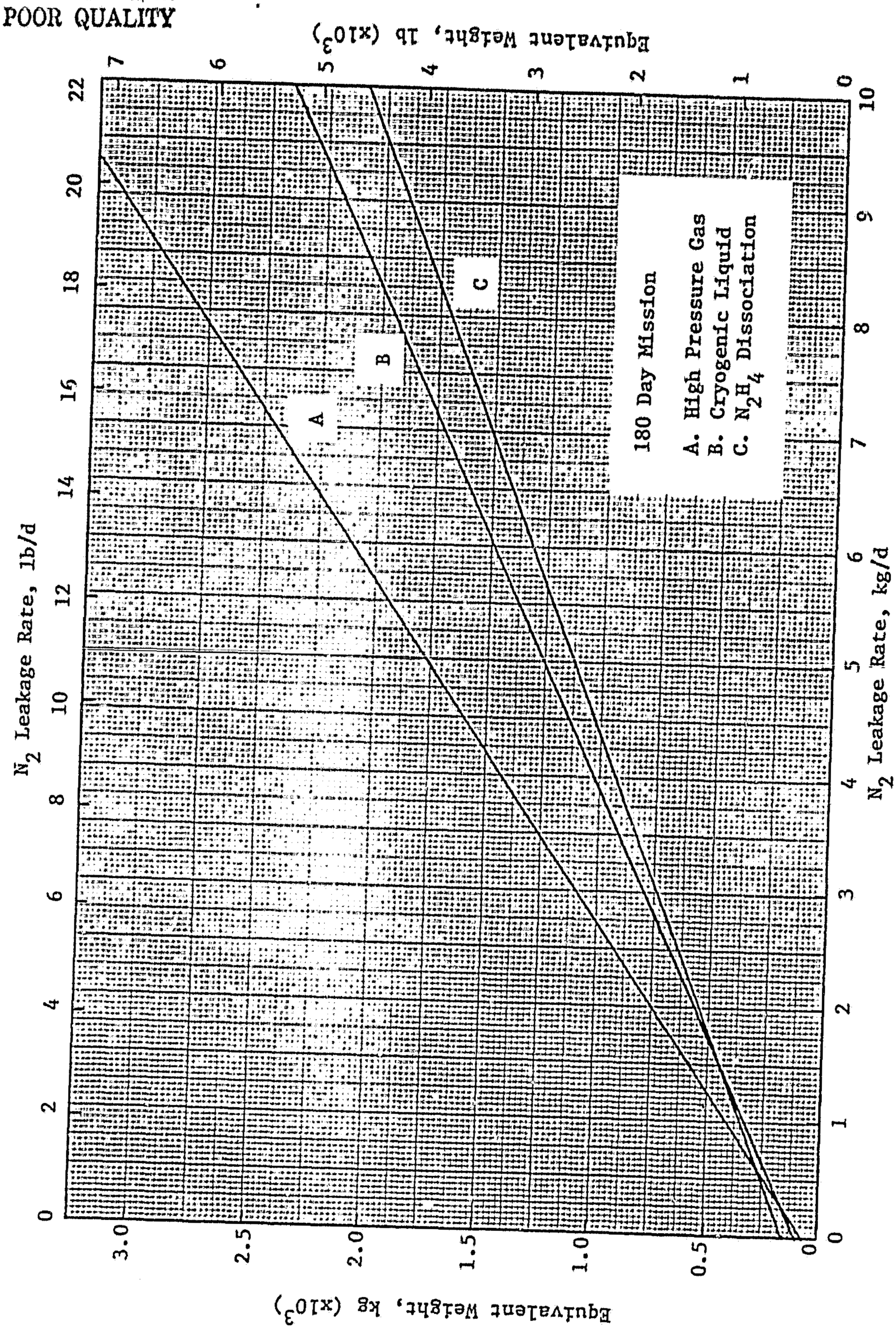


FIGURE 1 CANDIDATE NITROGEN SOURCE TRADE-OFF

Program Organization

To meet the above objectives the program was divided into five tasks plus the documentation and program management functions. The five tasks were:

1.0 Identify and evaluate alternate NGM sealing techniques and incorporate the preferred technique into the NGM prior to testing as a part of the NSS.

2.0 Provide the Test Support Accessories (TSA) to enable operation of the NSS with the ARX-1 during testing.

3.0 Establish, implement and maintain a Product Assurance Program throughout the contractual period to search out quality weaknesses and define appropriate corrective measures.

4.0 Perform a variety of tests on the NSS as an integrated subsystem within the ARX-1.

5.0 Complete those supporting technology activities required to support the development of the NGM and the NSS as part of a spacecraft Air Revitalization System (ARS).

Report Organization

This Final Report covers the work performed during the period December, 1978 through January, 1980. The following four sections present the technical results grouped according to (1) NGM Development, (2) NSS Development, (3) Mini-Product Assurance Program and (4) Supporting Technology Studies. These sections are followed by Conclusions and Recommendations based on the work performed.

NITROGEN GENERATION MODULE DEVELOPMENT

The NGM is the major component in an NSS based on the catalytic dissociation of liquid N_2H_4 and subsequent separation of the product gases into N_2 and H_2. The NGM combines all catalytic dissociation and subsequent Pd/Ag H_2 separation stages into a single unit. The objective of the prior development activities was to develop the initial NGM hardware required to (a) demonstrate and verify the staging concept and the single unit NGM design, and (b) experimentally generate a technology base that can be used to optimize subsequent advanced NGM designs.[2,4,5] Emphasis in these development activities, therefore, was placed on developing an NGM that could be used as a test bed to generate necessary design data. Only secondary emphasis was placed on minimizing NGM weight.

The recent NGM development activities have been directed toward incorporation of improved sealing techniques into existing NGM components with hardware modification as required. In the process, the weight of the NGM was reduced by redesign of the separator housing. Design considerations for integrating the NGM and NSS with the ARX-1 were included. The following sections review the NGM design concept and operation and summarize the hardware fabricated.

Design Description

The function of the NGM is to generate N_2 and byproduct H_2 from liquid N_2H_4. The NGM consists of alternate catalytic dissociation and H_2 separation stages configured to give high purity N_2 and H_2. The dissociator and separator stages are packaged as a single unit to minimize heat rejection to ambient since both operate at elevated temperatures. The single package concept also allows the heat generated during the dissociation of N_2H_4 to reduce the heater power required to maintain the NGM at operating temperature.

Concept Description

A block diagram showing the staging concept is presented in Figure 2. The NGM consists of one N_2H_4 dissociation stage, three ammonia (NH_3) dissociation stages and four H_2 separation stages. The N_2H_4 feed/N_2 product stream flows in series from stage to stage. The projected gas concentrations following each dissociation and H_2 separation stage demonstrate the method of obtaining low NH_3 and H_2 concentrations.

Hydrazine is catalytically dissociated in the first stage via the following reactions:[6]

$$N_2H_4 = 1/3\ N_2 + 4/3\ NH_3 \quad (1)$$

$$\underline{4/3\ NH_3 = 2/3\ N_2 + 2H_2} \quad (2)$$

$$N_2H_4 = N_2 + 2H_2 \quad (3)$$

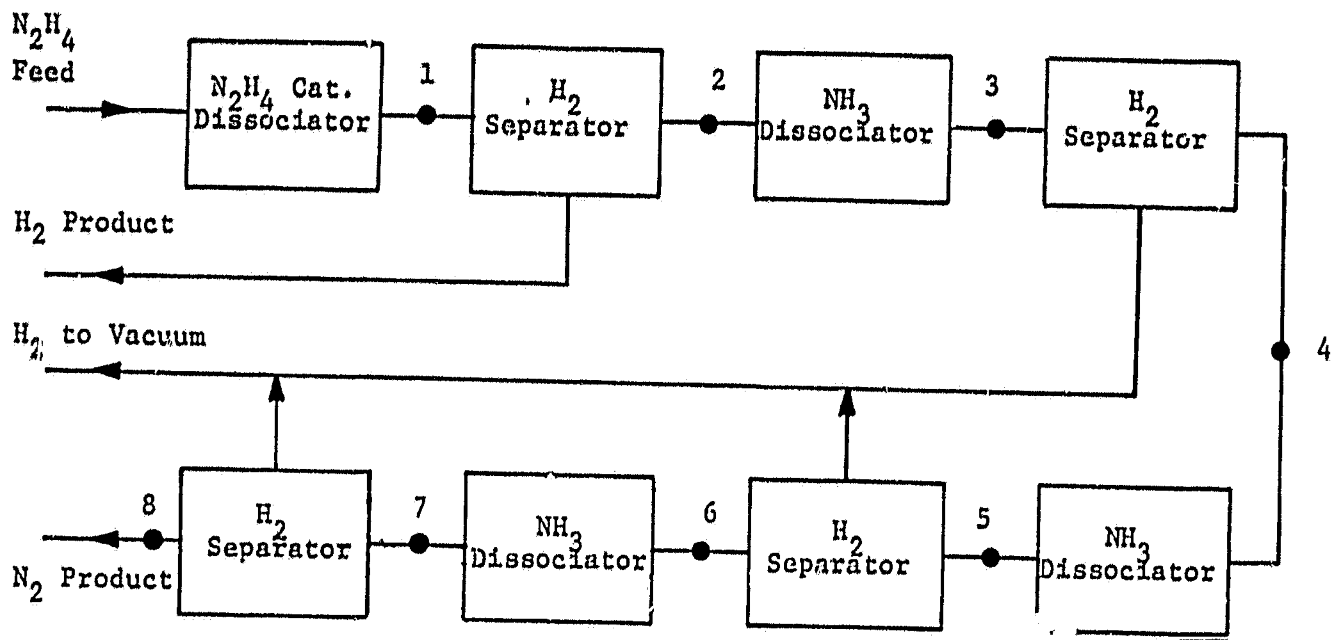
All the N_2H_4 is dissociated in this initial stage. Not all of the NH_3 formed by equation 1, however, is dissociated in the N_2H_4 catalytic dissociator.

The N_2, H_2 and unreacted NH_3 gases from the first stage enters the first H_2 separation stage. Most (90%) of the H_2 entering this stage is removed and collected at 172 kPa (25 psia) for use in the CO_2 Reduction Subsystem (CRS). The N_2 product gas from the first separation stage is then manifolded to the first NH_3 dissociation stage. The high NH_3 and N_2 concentrations entering the dissociator favor further NH_3 dissociation and the formation of more N_2 and H_2 (equation 2).

Alternate H_2 separation and NH_3 dissociation stages are used to attain the final N_2 product purity. The H_2 removed in the last three H_2 separation stages is vented to space vacuum and is therefore not available for use in the CRS. The H_2 separation to vacuum is required to attain the low H_2 concentration required in the product N_2.

Design Specifications

The NGM design specifications are presented in Table 1. The NGM was sized to deliver 3.64 kg/d (8.00 lb/d) of N_2 and 0.44 kg/d (0.96 lb/d) of H_2. The NH_3 concentration in the product N_2 is of prime concern in the NGM design since less than 50 ppm is required to satisfy contamination requirements for direct utilization of N_2 in a spacecraft cabin atmosphere. The requirement for less



Stream	% N_2	% H_2	% NH_3	Eff. %	Temp. K (F)
1	32.8	64.0	3.2	93	1000 (1340)
2	77.3	15.1	7.6	90	644 (700)
3	75.8	22.8	1.4	80	811 (1000)
4	96.7	1.5	1.8	95	644 (700)
5	95.9	4.0	0.09	95	811 (1000)
6	99.8	0.08	0.09	98	644 (700)
7	99.78	0.2	19 ppm	98	811 (1000)
8	99.9	0.1	19 ppm	50	644 (700)

FIGURE 2 NGM STAGING CONCEPT BLOCK DIAGRAM

TABLE 1 NGM DESIGN SPECIFICATIONS

Hydrazine Feed Rate, kg/d (lb/d)	4.15 (9.14)
Nitrogen Generation Rate, kg/d (lb/d)	3.64 (8.00)
Hydrogen Generation Rate, kg/d (lb/d)	0.44 (0.96)
Nitrogen Product Composition, Volume %	
Hydrogen	$\leq$0.2
Ammonia	$\leq 5 \times 10^{-3}$
Water[a]	$\leq$0.1
Hydrogen Byproduct Purity, Volume %	>99.9
Surface Temperature Guidelines, K (F)	$\leq$322 (120)

(a) The water concentration in the nitrogen product stream is caused by the small amount of water present in the hydrazine feed stream.

than or equal to 0.2% H_2 in the product N_2 is not as critical since lower H_2 concentrations have been demonstrated previously.[5] The final H_2 separation stage shown in Figure 2 maintains this requirement.

Operation

Figure 3 is a functional schematic of the NGM showing the orientation of the individual stages. The NGM performs three functions: N_2H_4 dissociation, NH_3 dissociation and H_2 separation. The temperatures of the dissociation stages and separation stages are controlled separately using two sets of heaters. Coolant N_2 is provided between the two temperature zones in the event cooling is required to control the two zones independently.

Hydrazine Dissociation

Hydrazine dissociation takes place in the center cavity of the NGM. Liquid N_2H_4 at a pressure of approximately 2070 kPa (300 psia) is injected into the dissociator through a capillary orifice in the header assembly. The diameter of the capillary opening is smaller than the quenching diameter for N_2H_4 to prevent propagation of the dissociation reaction back to the supply. In the feed orifice N_2H_4 is taken from a liquid at ambient temperature to a vapor slightly above the boiling point of N_2H_4 at the operating pressure.

Hydrazine vapor enters the central dissociator tube at an elevated temperature and dissociates autocatalytically. The central feed tube is packed with 10 to 20 mesh tungsten chips to allow heat to transfer to the gas phase which promotes the autocatalytic reaction. A platinum (Pt) screen is located at the end the central feed tube to ensure that any undissociated N_2H_4 reacts prior to entering the packed catalyst bed in the concentric annular housing.

At the end of the central tube the flow pattern of the product gases is reversed in direction. The product gases flow in the annular housing concentric with the central tube and exit at the hottest zone in the reactor. The decomposition of NH_3 into N_2 and H_2 (equation 2) is favored kinetically and thermodynamically at higher temperatures.[7] The hairpin-type reactor design will therefore result in higher NH_3 conversion efficiencies in the N_2H_4 dissociation stage. Tungsten catalyst retaining screens are used to prevent catalyst particles from being removed by the product gases. The product gas from the N_2H_4 dissociation stage is manifolded to the first H_2 separation stage.

Ammonia Dissociation

The three NH_3 dissociation stages are located in the central NGM core around the outside of the N_2H_4 dissociation stage. The product N_2 gas stream, enriched in N_2 and NH_3 after passing through a H_2 separation stage, is fed into a NH_3 dissociation stage at the same end of the NGM as the N_2H_4 feed. The product gas passes through the packed catalyst bed traveling the length of the dissociator core. At the end of the first catalyst bed the gases are manifolded to the second portion of the catalyst bed in the dissociation stage. The product gas then travels back the length of the reactor core and exits at the same end of the reactor as the feed stream. Each NH_3 dissociation stage, therefore, consists of two side-by-side tubes packed with catalyst.

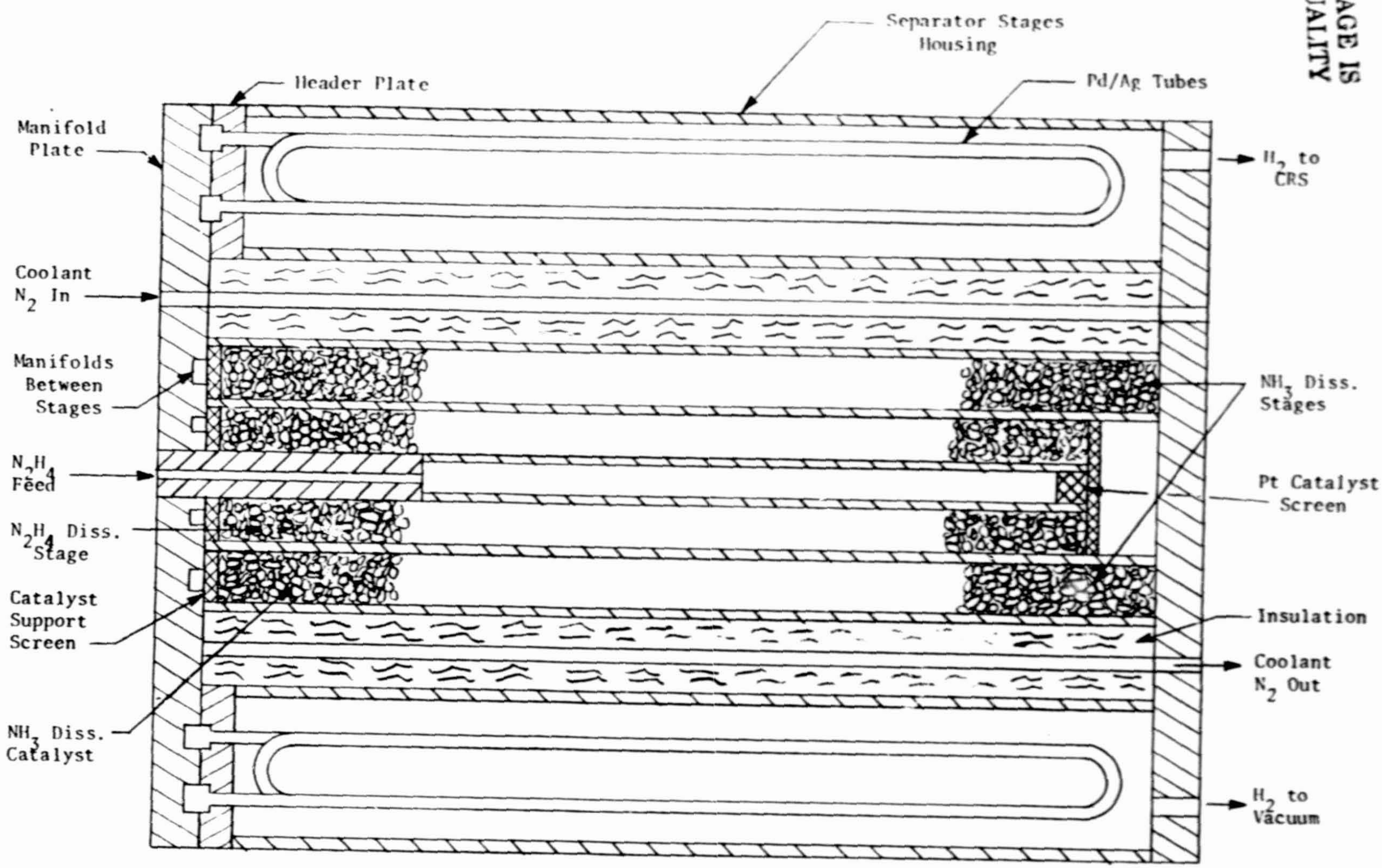


FIGURE 3 NGM FUNCTIONAL SCHEMATIC

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Hydrogen Separation

The four H_2 separation stages are located around the outside of the NGM. The Pd/Ag tubes are connected to a donut-shaped header plate and are thermally isolated from the central NGM core where N_2H_4 and NH_3 dissociation takes place. The reason for the thermal isolation is the difference in operating temperatures. The H_2 separation stages operate at 644 K (700 F) and the dissociator core is maintained at 1000 K (1340 F).

The H_2 separation stages are connected to the main manifold plate which manifolds the process gases between the H_2 separation and the dissociation stages. The N_2/H_2 mixture from a dissociation stage enters the inside ends (i.e., closest to the center of the NGM) of Pd/Ag tubes in the stage. The process gas passes through all of the Pd/Ag tubes in each individual stage in parallel. The H_2-depleted gas stream from a H_2 separation stage is then manifolded from the outside ends of the tubes to the next NH_3 dissociation stage.

In the first H_2 separation stage, H_2 is collected at less than or equal to 172 kPa (25 psia) for use in the CRS. The H_2 removed in the second, third and fourth H_2 separation stages exhausts the NGM through a common manifold and is vented to vacuum.

Temperature control of the H_2 separation stages is provided through metal ribs which connect the outside and inside concentric cylinders which form the housing for the separation stages. Band heaters located on the outside wall are able to transmit heat to the inside surface through these ribs, thereby keeping the Pd/Ag tubes at a constant temperature.

Operating Conditions

Table 2 gives the projected steady-state operating conditions for the NGM. The dissociation stage and separation stage temperatures are controlled using three cartridge heaters located in the dissociator core and six band heaters located around the outside of the H_2 separator housing. Thermocouples located within the NGM are used to provide closed-loop temperature feedback control. The dissociator core is controlled at 1000 K (1340 F) and the Pd/Ag separator tubes are controlled at 644 K (700 F). In addition to the heaters, a port for N_2 coolant gas is provided between the dissociator core and the H_2 separator stages in the event that the Pd/Ag tubes should start to overheat due to the heat generation in the dissociator core.

As part of the developmental effort, an improved H_2 separator stage for the NGM was designed and developed. This improved hardware includes a housing, manifold endplate and Pd/Ag tube header plate. The separator design also incorporated a new sealing technique. The dissociator assembly was retained from prior contractual work.

Hardware Description

Front and rear views of the assembled NGM are presented in Figures 4 and 5, respectively. Figure 6 shows the disassembled NGM hardware while views of the disassembled dissociation and separator stages are shown in Figures 7 and 8, respectively. The NGM consists of ten major subassemblies/components. These

TABLE 2 NGM NOMINAL OPERATING CONDITIONS

Catalytic Dissociator Temperature, K (F)	1000 (1340)
Pd/Ag Separator Temperature, K (F)	644 (700)
Hydrazine Feed	
Source	Liquid Hydrazine
Hydrazine Flow Rate, kg/d (lb/d)	4.15 (9.14)
dm^3/min	2.9
Composition, Weight %	
Hydrazine	99.5 to 100
Water	0 to 0.5
Temperature, K (F)	291 to 297 (65 to 75)
Pressure, kPa (psia)	1794 (260)
Nitrogen Product	
Flow Rate, kg/d (lb/d)	3.64 (8.0)
dm^3/min (cfm)	2.2 (0.078)
Composition, Volume %	
Hydrogen	0.2
Ammonia	1.9×10^{-3}
Water	<0.1
Temperature, K (F)	644 (700)
Pressure, kPa (psia)	1725 (250)
Hydrogen Byproduct	
Flow Rate, kg/d (lb/d)	0.44 (0.96)
dm^3/min (cfm)	3.6 (0.13)
Purity, Volume %	99.9999 to 100
Temperature, K (F)	644 (700)
Pressure, kPa (psia)	172 (25)
Hydrogen Vented	
Flow Rate, kg/d (lb/d)	0.08 (0.18)
dm^3/min (cfm)	0.68 (0.024)
Temperature, K (F)	644 (700)
Pressure, Pa (mm Hg)	0 to 1330 (0 to 10)
Coolant Supply	
Type	Ambient Air or N_2
Temperature, K (F)	291 to 297 (65 to 75)
Flow Rate, cm^3/min (cfm)	28 (1)
Cabin Environment Data	
Operational Gravity, m/s^2 (G)	0 to 9.8 (0 to 1.0)
Total Pressure, kPa (psia)	101 (14.7)
Oxygen Partial Pressure, kPa (psia)	21.4 (3.1)
Diluent	N_2
Hydrogen Concentration, Volume %	0.2
Ammonia Concentration, Volume %	5.0×10^{-5}
Temperature, K (F)	291 to 297 (65 to 75)

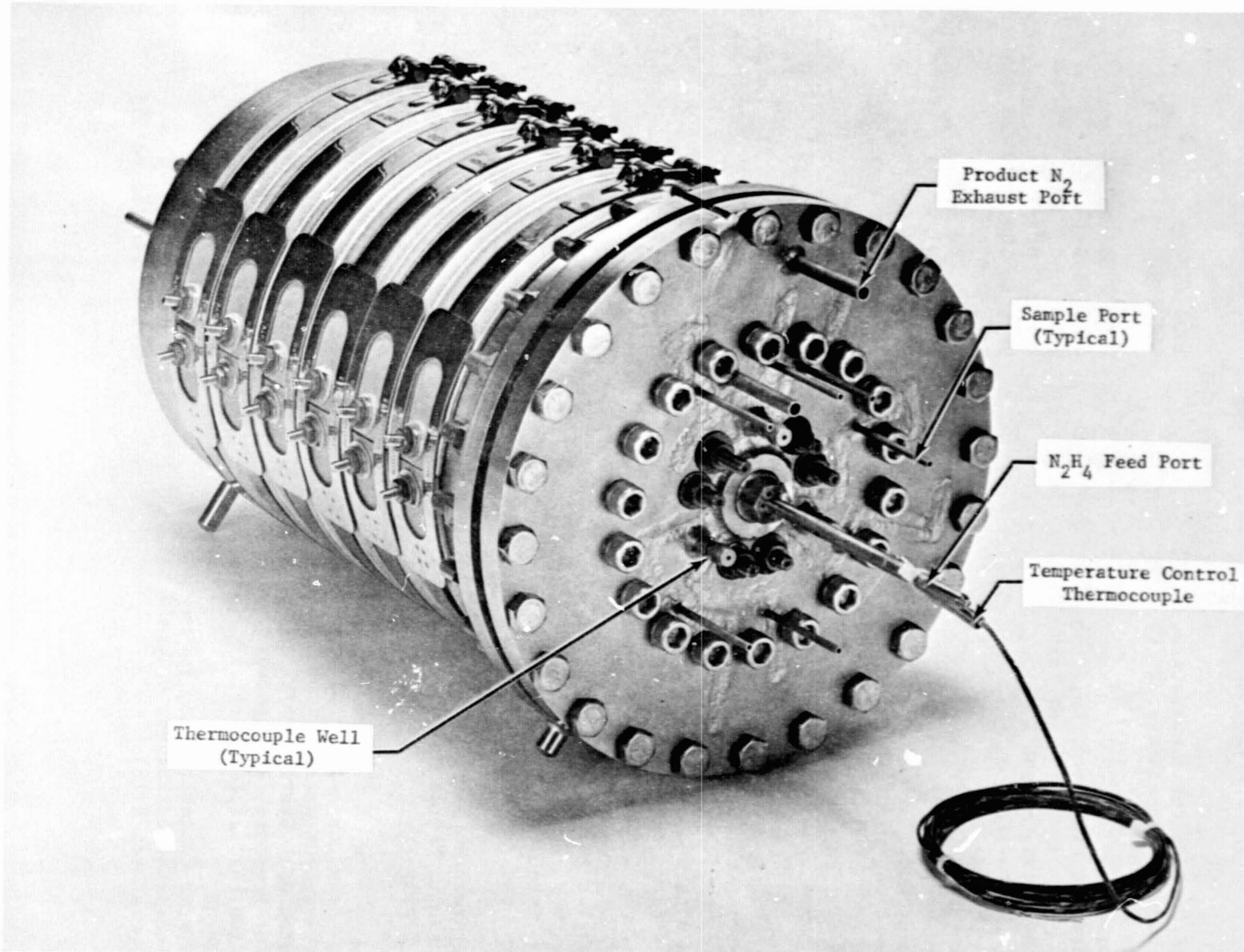


FIGURE 4 ASSEMBLED NGM (FRONT VIEW)

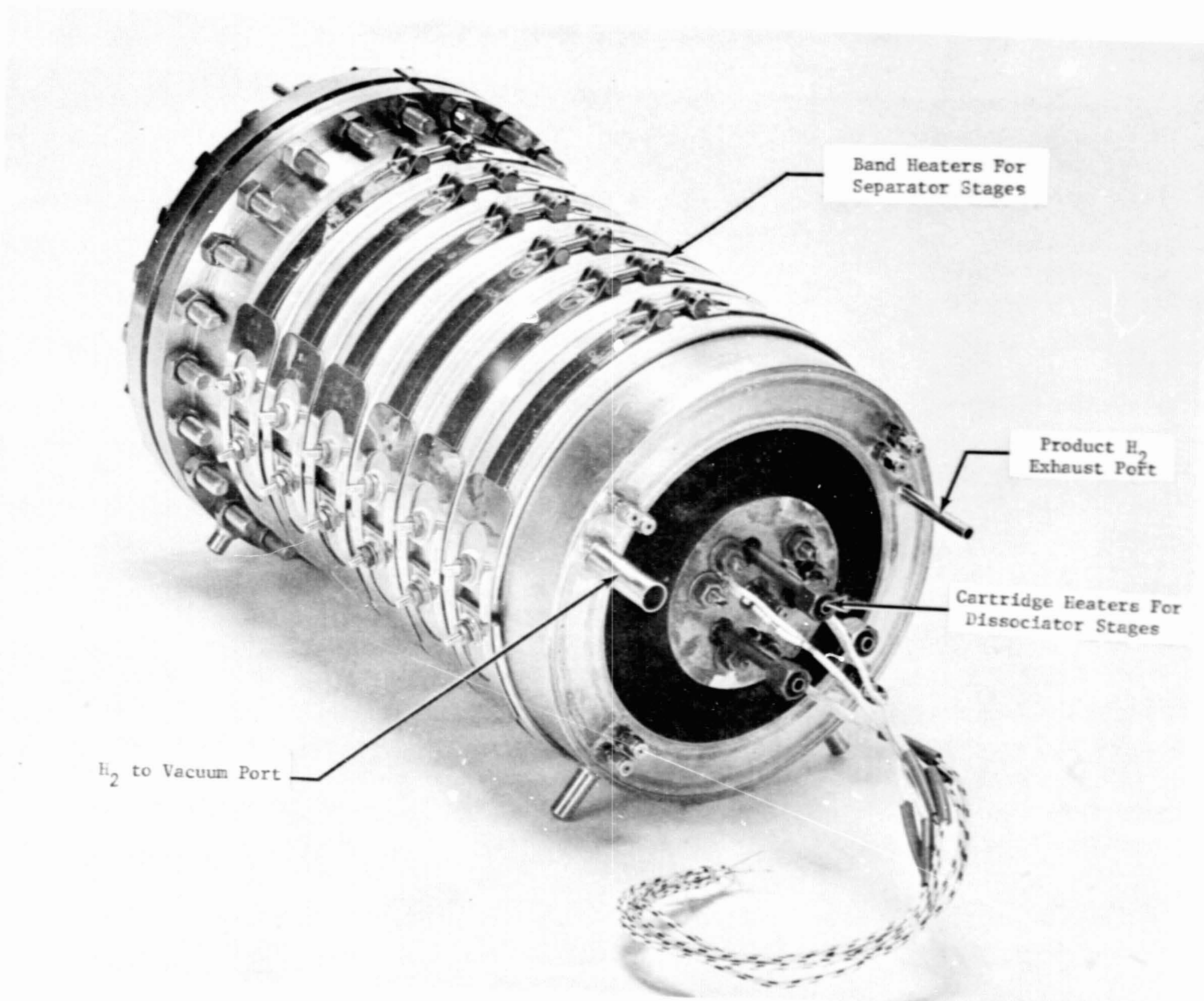


FIGURE 5 ASSEMBLED NGM (REAR VIEW)

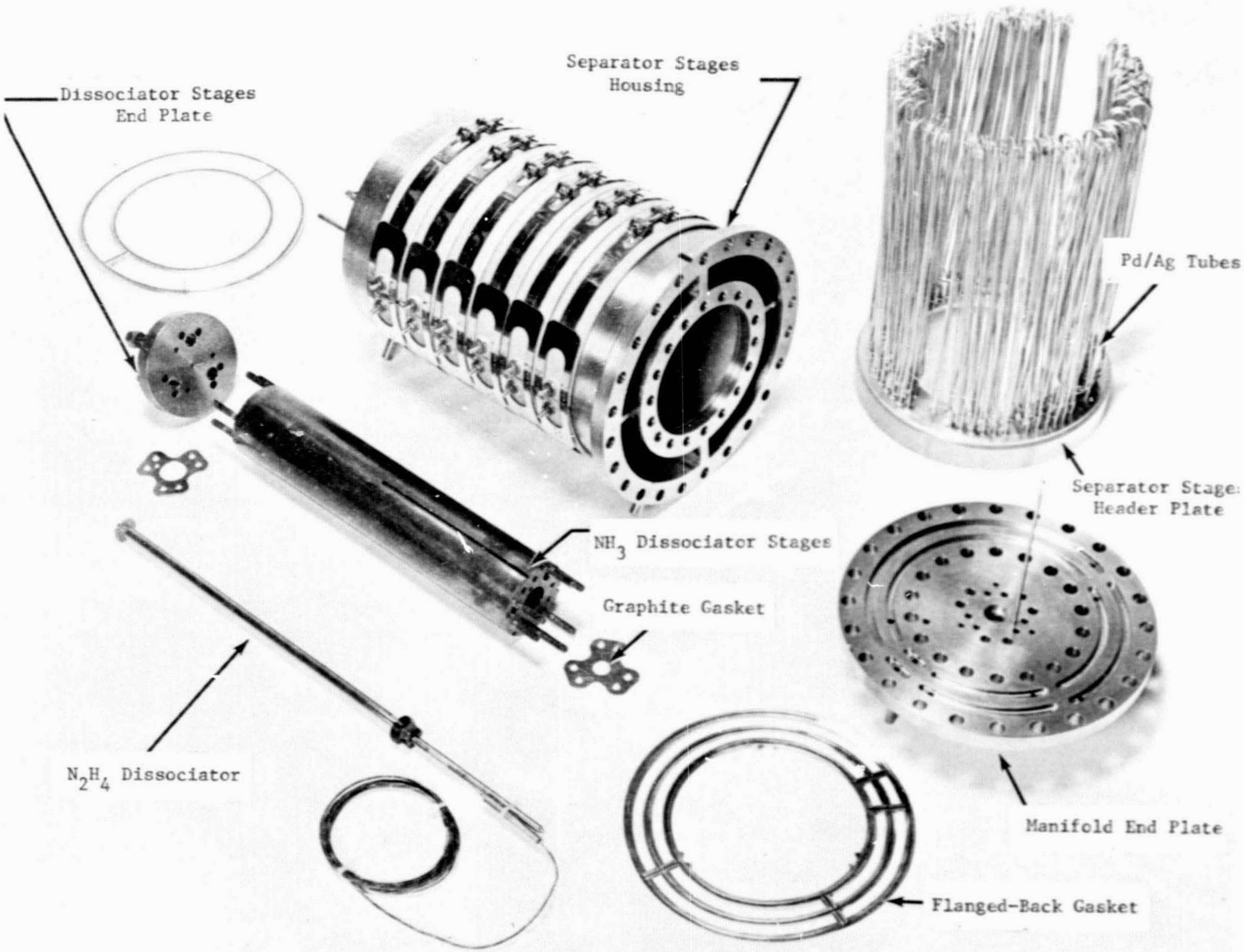


FIGURE 6 DISASSEMBLED NGM

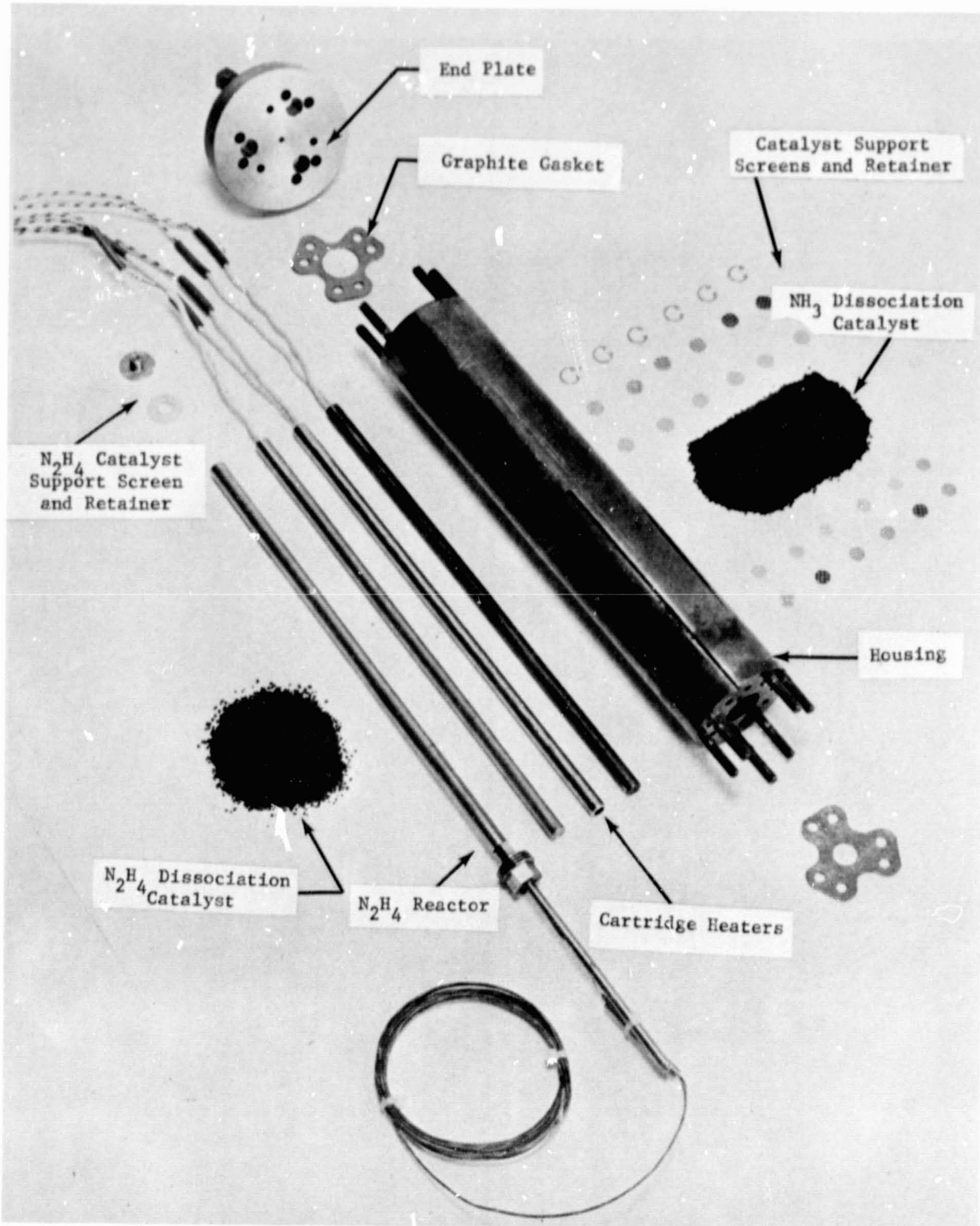


FIGURE 7 DISSOCIATOR STAGES (DISASSEMBLED)

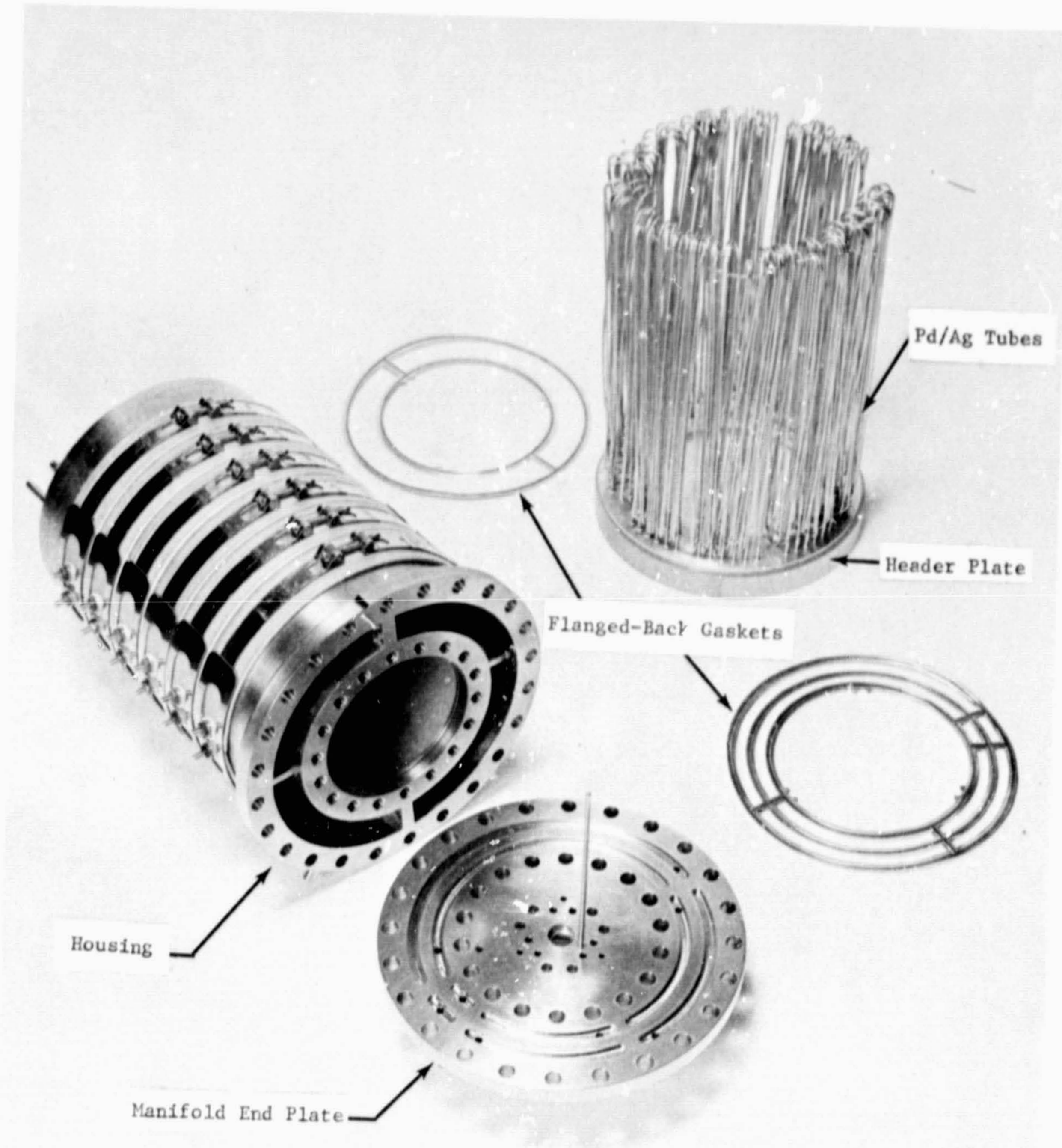


FIGURE 8 SEPARATOR STAGES (DISASSEMBLED)

subassemblies/components are summarized in Table 3. The NGM hardware description is summarized in the following sections through a discussion of the individual design considerations.

Operational Flexibility

Since the NGM is used to generate performance and design data for future NGM designs, maximum flexibility in the design and operation of the NGM was required. The capability to monitor individual stage performance and temperature distribution profile data, and to individually control separator and dissociator stage temperatures was incorporated into the design to provide testing flexibility. Gas sample taps between each stage were incorporated to allow a sample to be analyzed thereby quantifying individual stage performance during integrated operation. The NGM temperature distribution profile is monitored through the incorporation of 16 thermocouples which provide for both radial and axial temperature profiles. Separate temperature control of the dissociation stages and separator stages is provided through heaters which are connected to feedback temperature controls. An N_2 cooling source is also provided should it be necessary for temperature control.

One additional design flexibility was required in the N_2H_4 dissociation stage. The NGM was designed to incorporate different N_2H_4 dissociator designs. The N_2H_4 dissociator can be maintained from the end plate. The N_2H_4 dissociator threads into the end plate and sealing is provided using a C-ring.

Maintainability

Maintainability is not a requirement of a flight version NGM. Maintainability, however, for the NGM fabricated for development testing under the present effort was required for testing flexibility. Operation at elevated temperatures and pressures, and the dimensional tolerances required for adequate sealing make disassembly and maintainability difficult. Operation at elevated temperatures causes the metal surfaces to adhere to each other through oxidation and scaling. Operation at elevated pressures and the large surface area required for sealing cause the sealing force required to be high.

The NGM was divided into ten major subassemblies and components for disassembly during maintenance. Sealing between the subassemblies is provided by graphite or flange-backed gaskets. Bolts are used to hold these subassemblies together and provide the sealing force required. Eventual NGM hardware could have completely welded joints eliminating the need for seals.

Temperature Control/Distribution

Heat is (a) generated in the N_2H_4 dissociation process, (b) required for the NH_3 dissociation process and (c) lost to ambient since the surface of the NGM (the H_2 separator stages) is at 644 K (700 F). The NGM has two distinct temperature zones. The H_2 separator stages operate at 644 ±28 K (700 ±50 F). The separation process is favored by higher temperatures but temperatures above 700 K (800 F) can decrease the reliability and life of the Pd/Ag tubes. The NH_3 dissociation stages require temperatures greater than or equal to 811 K (1000 F). The center of the dissociator housing (i.e., the N_2H_4 dis-

TABLE 3 NGM SUBASSEMBLIES/COMPONENTS

Subassembly/Component	Number Required
Housing, Separation Stages	1
Header Plate (with Pd/Ag Tubes)	1
End Plate, Manifold	1
Gaskets, Flanged-Back, Separator	2
End Plate, Dissociation Stages	1
Dissociator, Hydrazine	1
Gaskets, Graphite, Dissociator	2
Housing, Dissociation Stages	1
Heaters, Cartridge	3
Heaters, Band	6

sociation stage) operates at approximately 1000 K (1340 F). The temperature then decreases to 811 K (1000 F) at the surface of the dissociator core.

Thermal control of the two separate zones is provided by three cartridge heaters located in the dissociator core and six band heaters located around the outside of the separator stages' housing. Separate feedback temperature control circuits are used to control the two temperature zones. Between the two zones, an ambient air insulation jacket is provided because of the large temperature difference. A cooling gas port is also provided between the dissociator core and the separator housing to prevent excessive temperatures. The objective, of course, is to minimize heater power and, eventually with further development, eliminate the need for any heater power. A passive thermal design is desired in which all heat required (that which is lost to ambient) is generated by the N_2H_4 dissociation process and each temperature zone is maintained without controls.

Since the dissociator core is made from a single piece of metal, minimum thermal gradients occur. The temperature profile throughout the dissociator core is evenly distributed, being hottest in the center and decreasing to the surface. The housing for the separator stages is made of two concentric cylinders which are connected by ribs to separate the individual stages. These ribs not only provide stage separation for the collected H_2 and structural support but also allow heat conduction between the two cylinders. The band heaters are located on the outside surface of the NGM. Should heat be required to maintain the temperature of the separator stages, it must conduct through these ribs to the inner surface. The ribs in the current design maintain the temperature of the separator stages at all points to within ±28 K (±50 F).

The two separate temperature zones cause one additional design problem; thermal expansion of the metals involved when controlling the different temperatures could cause sealing problems. The staging process alternately uses separator and dissociator stages and therefore a manifold technique is still required to connect the two temperature zones. The present design accommodates the different thermal expansion rates by connecting the dissociator and separator stages to a manifold end plate on one end only, but using separate welded end plates on the other end. The separate end plates allow the hotter dissociator core to expand more than the separation stages, thereby eliminating sealing and possible mechanical failure problems.

Sealing

Sealing between the various NGM stages was necessitated by the maintainability requirements. The sealing requirements for the NGM are differential pressures of 1720 kPa (250 psia) to vacuum, compatibility with elevated temperatures (up to 1000 K (1340 F)), compatibility with a corrosive NH_3, H_2 and N_2 atmosphere and irregular (noncircular) sealing surface geometries. These sealing criteria limited the selection of a sealing method to graphite gaskets. Graphite gaskets have been used for high-temperature sealing applications and meet the temperature and compatibility requirements. Vendor data indicated that a flat graphite gasket would be capable of handling the sealing requirements without problems. The graphite gasket sealing technique was therefore initially selected.

After fabrication of the NGM and the graphite gaskets, initial sealing tests uncovered problems of cold flow and fracturing of the graphite gasket sealing material. Design data offered by the vendor indicated that there would be no cold flow problems using the graphite gaskets. Further investigation, however, showed that cold flow problems did occur. Minor gas leakage was also uncovered and appeared to be diffusion through the graphite gasket material itself. Upon dissassembly of the NGM it was discovered that the graphite gasket material was not reusable as it strongly adhered to the metal surfaces in contact with it. Upon disassembly, the gasket was pulled apart making reuse impossible.

A solution to the sealing problems was the use of a flanged-back graphite gasket. A major effort of this program was the selection, test and procurement of the flanged-backed gasket. Additional discussion of this new seal is found in the Supporting Technology section. Seals made from the flanged-backed gaskets proved successful.

Materials of Construction

A detailed list of all NGM parts and their compatibility requirements (environment) was prepared prior to fabrication. The major materials considerations required for the NGM are compatibility with the process gas and operation at elevated temperatures. The thermal expansion properties of all materials were also considered. The primary materials compatibility problems faced were corrosion due to N_2H_4 and NH_3, nitrification and H_2 embrittlement. All materials used passed the required materials standards.

Manifolding Between Stages

All manifolding of the N_2 product gas stream between the various separation and dissociation stages was accomplished using a single manifold end plate. This single plate at one end of the module helped eliminate thermal expansion problems caused by the different NGM temperature zones. All N_2 process gas streams therefore enter and leave a stage at the same end of the NGM. The H_2 byproduct and vent-to-vacuum streams which do not require manifolding between stages are collected from the shell side of the separator stage housing at the opposite end of the NGM.

Interfaces

The NGM has five mechanical interfaces and two electrical interfaces. The mechanical interfaces are the N_2H_4 liquid feed stream, the N_2 product stream, the H_2 byproduct, the H_2 vented to vacuum and the N_2 coolant supply. The electrical connections include power to the heaters and the temperature sensor connectors. The NGM contains eight temperature sensors; two are used for control and six are used for fault detection and isolation. The NGM also has provisions for an additional eight thermocouples for temperature profile mapping during development testing.

NITROGEN SUPPLY SUBSYSTEM DEVELOPMENT

The primary function of the NSS is to generate N_2 for cabin leakage makeup thereby controlling total cabin pressure. The NSS is an integratable subsystem within a central ARS. For an ARS based on Sabatier CO_2 reduction, the byproduct H_2 generated by the NSS is used to increase CO_2 reduction efficiency. The NSS can be divided into two parts consisting of those components located within the central ARS (i.e., the inhabited cabin), and the N_2H_4 storage and feed assembly which is located separately and most likely in common with other spacecraft N_2H_4 storage (e.g., an uninhabited or unpressurized area).

The objectives of the development activities described in this report were to (a) assemble and check out the N_2H_4 storage and feed mechanism as an assembly separate from the NSS components located within the ARS, (b) assemble, check out and test the peripheral mechanical and electrical components required to control and monitor subsystem performance for operation with the ARX-1, (c) integrate the NSS, including the NGM, within the ARX-1, (d) check out the computer-based instrumentation hardware and software components required to interface the NSS with the ARX-1 and (e) perform integrated testing of the NSS. The following sections review the NSS design, describe the ARX-1 and the NSS/ARX-1 integration, describe the TSA required for operating the NSS as part of the ARX-1 and summarize the testing performed.

Nitrogen Supply Subsystem Design

The NSS was designed as an integratable subsystem for a central ARS. Those components which would be redundant in another ARS subsystem have been eliminated in the NSS. In addition, certain functions that would be performed by the NSS for the entire central ARS have been included. The NSS consists of the N_2H_4 storage and feed mechanism, the NGM, the peripheral mechanical and electrical components required to control and monitor subsystem performance, and the advanced instrumentation required for the NSS to interface with other ARS subsystems and controls.

Design Specifications and Features

The NSS was designed to deliver N_2 at a rate of 3.64 kg/d (8.00 lb/d) at pressures less than or equal to 1725 kPa (250 psia). The design specifications for the NSS are listed in Table 4.

The overall goal of the design effort was to design an NSS as an integrated subsystem within a central ARS. The design features incorporated, therefore, were selected based on both subsystem and integrated system (ARX-1) design requirements. The following is a list of the major design features incorporated.

1. The subsystem components were developed for assembly within an integrated ARS as opposed to a separate subsystem interface.

2. A separate N_2H_4 storage and feed mechanism assembly was designed to simulate that portion of the NSS that would be located outside the habitable cabin.

TABLE 4 NITROGEN SUPPLY SUBSYSTEM DESIGN SPECIFICATIONS

Leakage Data	
Air Leakage Rate, kg/d (lb/d)	4.74 (10.4)
Nitrogen Leakage Rate, kg/d (lb/d)	3.64 (8.00)
Oxygen Leakage Rate, kg/d (lb/d)	1.10 (2.43)
Cabin Atmosphere Data	
Operational Gravity, m/s^2 (G)	0 to 9.8 (0 to 1)
Total Pressure, kPa (psia)	101.3 (14.7)
Oxygen Partial Pressure, kPa (psia)	21.4 (3.1)
Diluent	Nitrogen
Volume	
Initial, m^3 (ft^3)	439 (15,500)
Growth, m^3 (ft^3)	960 (33,900)
Ventilation Rate	
Minimum, cm/s (ft/min)	7.6 (15)
Maximum, cm/s (ft/min)	20.3 (40)
Hydrogen Concentration, Volume %	0.2
Ammonia Concentration, Volume %	5.0×10^{-3}
Temperature, K (F)	291 to 297 (65 to 75)
Surface Temperature Guidelines, K (F)	<322 (120)
Acoustical Guidelines	NC-65

3. The byproduct H_2 generated can be used by a Sabatier reactor for CO_2 reduction.

4. The NSS has self-contained, fully-automated controls.

5. Control and monitoring functions are provided by computer-based instrumentation utilizing software programming techniques.

6. Four steady-state operating modes were incorporated.

7. The mode transition sequences were integrated into the sequencing required for operation of the ARX-1.

8. Manual overrides and controls have been included for off-design testing.

9. Redundant N_2H_4 storage tanks were developed to simulate the controls required to automatically switch tanks as required in actual flight application.

10. Redundant automatic shutoff valves were used on the N_2H_4 feed line for projected flight safety and maintenance requirements.

11. All materials of construction used are compatible with their environment.

Subsystem Operation

Figure 9 is a block diagram of the NSS. High pressure N_2 at 2070 kPa (300 psia) is used to pressurize the N_2H_4 storage tanks. Hydrazine is forced from the tanks through a flow control which controls the N_2H_4 feed rate to the NGM by adjusting the feed pressure to the tanks. The N_2 and H_2 product streams are cooled in air heat exchangers prior to exiting the subsystem. The N_2 product pressure is controlled at 1725 kPa (250 psia) by a backpressure regulator. The H_2 vent-to-vacuum stream from the second, third and fourth H_2 separation stages in the NGM is not cooled prior to exiting the subsystem. The absolute mass flow rate and heat capacity in the stream is very small and the gas stream will reach ambient temperature in just the length of tubing through which the stream exits the subsystem.

Solenoid valves are provided on the two N_2H_4 tanks to allow continuous operation of the NSS. One tank is always operating while the other tank remains in standby. As the first tank is emptied, the second tank is switched on-line and the first tank is isolated for refilling.

Solenoid valves and flow control orifices are used to distribute the high pressure N_2 for purging the three process gas streams. Solenoid valves on the H_2 vent-to-vacuum and N_2 product streams allow all purge gas to be vented through the H_2 byproduct stream which would be connected to the CRS. As part of an integrated ARS, the CRS would handle the purge vent for all ARS subsystems to prevent duplication of valving required to exhaust purge gas to space vacuum. The H_2 vent-to-vacuum requirements would be handled similarly as part of the ARS so duplication is not required in the NSS.

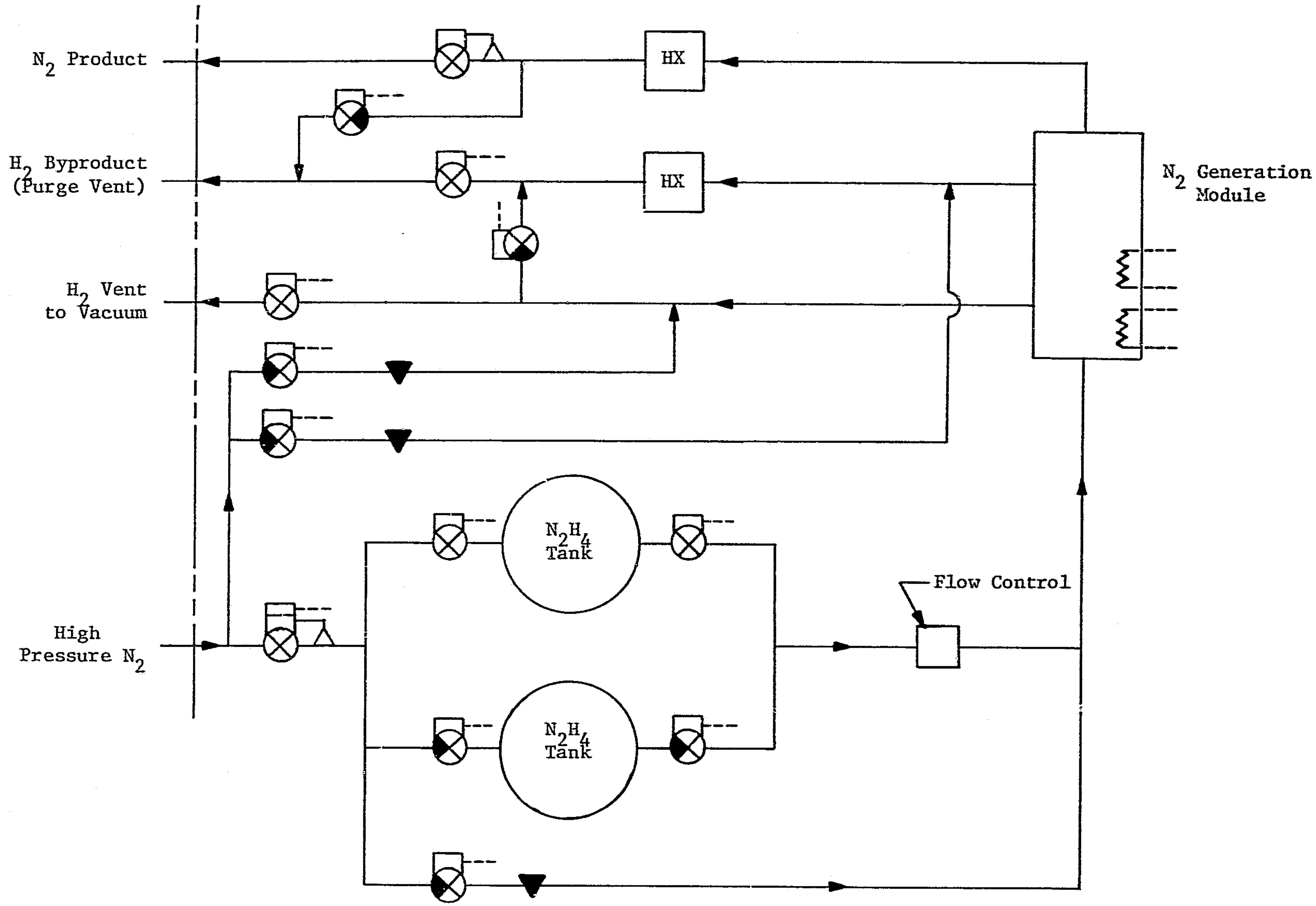


FIGURE 9 NITROGEN SUPPLY SUBSYSTEM BLOCK DIAGRAM

The detailed schematic of the NSS, presented in Figure 10, shows the specific valves and sensors that are used in the NSS. The component identification (e.g., V31, P18) are consistent with the overall ARX-1 designation scheme. The N_2 pressure to the supply tanks is controlled using a motor-driven regulator (V30) and a closed-loop feedback control from pressure sensor P23. The pressure is controlled at a level to maintain a desired N_2H_4 flow rate through flow control Q8 as measured by the differential pressure across the fixed orifice.

The N_2H_4 storage tanks are shown as being located in a nonhabitable compartment of the spacecraft. Hydrazine stored on-board a spacecraft would be fed to the NSS from outside the inhabited cabin atmosphere.

Manual valves (MV2 through MV6) are provided to refill the tanks since each supply tank was sized to last approximately five days. Solenoid valves V32 through V35 determine which tank is on-line. The control instrumentation automatically alerts the operator when a tank needs to be refilled and automatically switches in the reserve tank. Pressure sensors and orifices are used to measure the amount of N_2H_4 in the reserve tank prior to switching to the reserve tank. This prevents switching in an N_2H_4 tank which has not been filled. The concept works on the principal of timing how long it takes to pressurize the tanks with N_2 pressure through a fixed resistance flow orifice. A very short pressurization time (less than one second) would indicate that the tanks were relatively full whereas a longer pressurization period (four minutes) would indicate the tanks are almost empty.

Redundant solenoid valve V27 and manual valves MV4 and MV7 are used as a safety precaution to ensure that during a shutdown the N_2H_4 feed stream is disconnected from the NGM both automatically and manually. Nitrogen purge is provided though solenoid valves V28, V29 and V31. Solenoid valve V31 also serves the dual purpose of prepressurizing the NGM prior to startup. Various pressure, temperature and flow sensors are located throughout the subsystem for sequencing control and fault isolation and detection.

The N_2 generated by the NSS is vented to the cabin through pressure regulator RE1 for cabin leakage makeup. The high pressure N_2 stream (upstream of regulator RE1) is also used for pressurization and purge purposes in other ARX-1 subsystems. The spacecraft N_2 supply is used to both pressurize the NSS during startup and purge other ARX-1 subsystems during startup and shutdown.

NSS/ARX-1 Integration

The NSS was designed to be an integratable subsystem for a central ARS. A one-person, experimental breadboard ARS, termed the ARX-1, was previously developed under NASA Ames Research Center and Contractor funding.[8] The integration of the NSS with the ARX-1 performed under this program completed the breadboard ARX-1. A self-contained system (versus subsystem) approach was selected for the ARX-1 based on reducing subsystem interfaces, eliminating redundant components and utilizing the products (i.e., heat, electrical power, fluids) of one subsystem in another. As an example, the H_2 generated by the NSS is used by the Sabatier based CO_2 Reduction Subsystem (S-CRS). Also, the Control/Monitor Instrumentation (C/M^2I) was designed as a single unit that would operate all components as a single system by providing for one-button startup/shutdown of all ARS functions, automatic sequencing and control and monitoring for self-protection and safe operation.

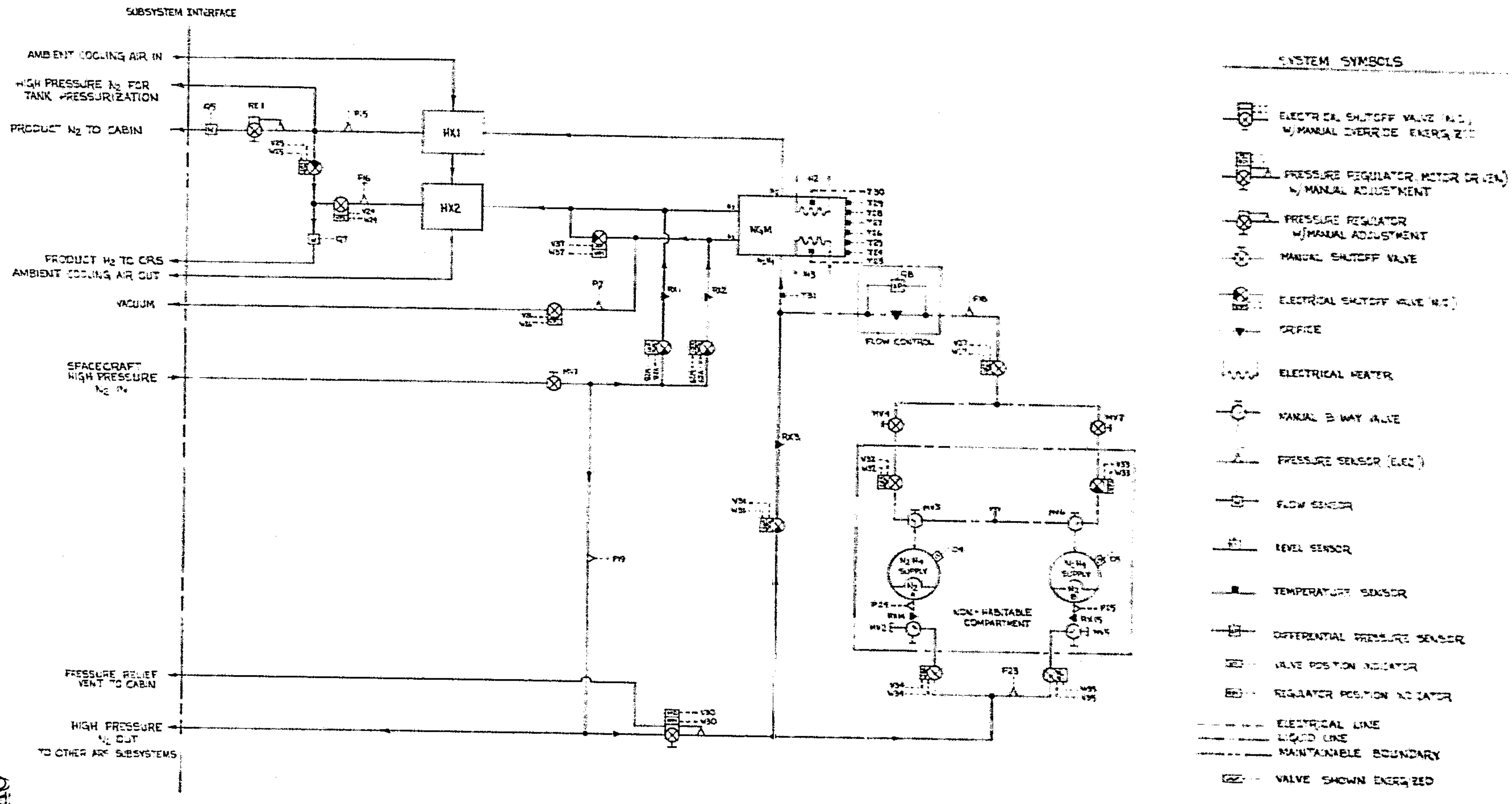


FIGURE 10 NITROGEN SUPPLY SUBSYSTEM SCHEMATIC

Figure 11 is a block diagram of the self-contained ARS concept. The NSS using decomposition of N_2H_4 provides for N_2 lost through cabin leakage. Also, the NSS supplies extra H_2 required by the S-CRS. The Oxygen Generation Subsystem (OGS), Electrochemical Depolarized CO_2 Concentrator (EDC) and S-CRS provide O_2 to and remove CO_2 from the crew space. Additional subsystems and components are needed to provide other air revitalization functions. A Cabin Humidity Control Subsystem (CHCS) is used to supply conditioned air to the EDC at a humidity level which results in optimum efficiency and to remove the metabolically- and EDC-produced moisture from the cabin air. A Water Handling Subsystem (WHS) collects, stores and distributes process water to the OGS. Finally, a centralized C/M I provides for automatic, integrated operation. Table 5 lists the design requirements established for the ARX-1. Of particular note is the net O_2 generation rate which includes O_2 for crew consumption and a provision for overboard leakage and EDC consumption.

Hardware Description

The mechanical hardware of the ARX-1 was packaged as a single unit as shown in Figure 12. Identified in Figure 12 are the NGM, the Sabatier reactor and modules of the EDC and OGS. Components of the WHS are distributed throughout the system. This breadboard system has a total weight of 281 kg (619 lb) and occupies an envelope of 71 x 96 x 114 cm (28 x 38 x 45 in). The ARX-1 mechanical hardware with its C/M I and TSA, which comprise the test facility, is shown in Figure 13. A detailed flow schematic of the ARX-1 is given in Figure 14.

The C/M I of the ARX-1 employs an advanced instrumentation concept which is highlighted by minicomputer-based controls and monitors. The C/M I was packaged in a separate enclosure shown in Figure 15. The function of the C/M I is to provide automatic mode and mode transition control, automatic shutdown provisions for self-protection, system parameter monitoring and ground test instrumentation interface.

Control and Monitor Instrumentation

The C/M I provides for automatic control and monitoring of the ARX-1 operation. Through a combination of minicomputer, analog circuitry hardware and assembly language software, all functions of mode and mode transition control, automatic shutdown, monitoring of system parameters and TSA interfacing were provided. The following describes details of the C/M I design and operation with emphasis on the portions which relate to the NSS.

The function of the C/M I is to provide:

1. Automatic mode control and mode transitions.
2. Automatic shutdown provisions for self-protection.
3. Provisions for monitoring critical parameters.
4. An interface with TSA instrumentation.

The ARX-1 has five operating modes: Shutdown, Normal, Standby, Purge and Unpowered. The five modes and the allowable mode transitions are shown in Figure 16. There are eight allowable mode transitions that can be programmed or commanded during NSS/ARX-1 operation. In the event of a power failure,

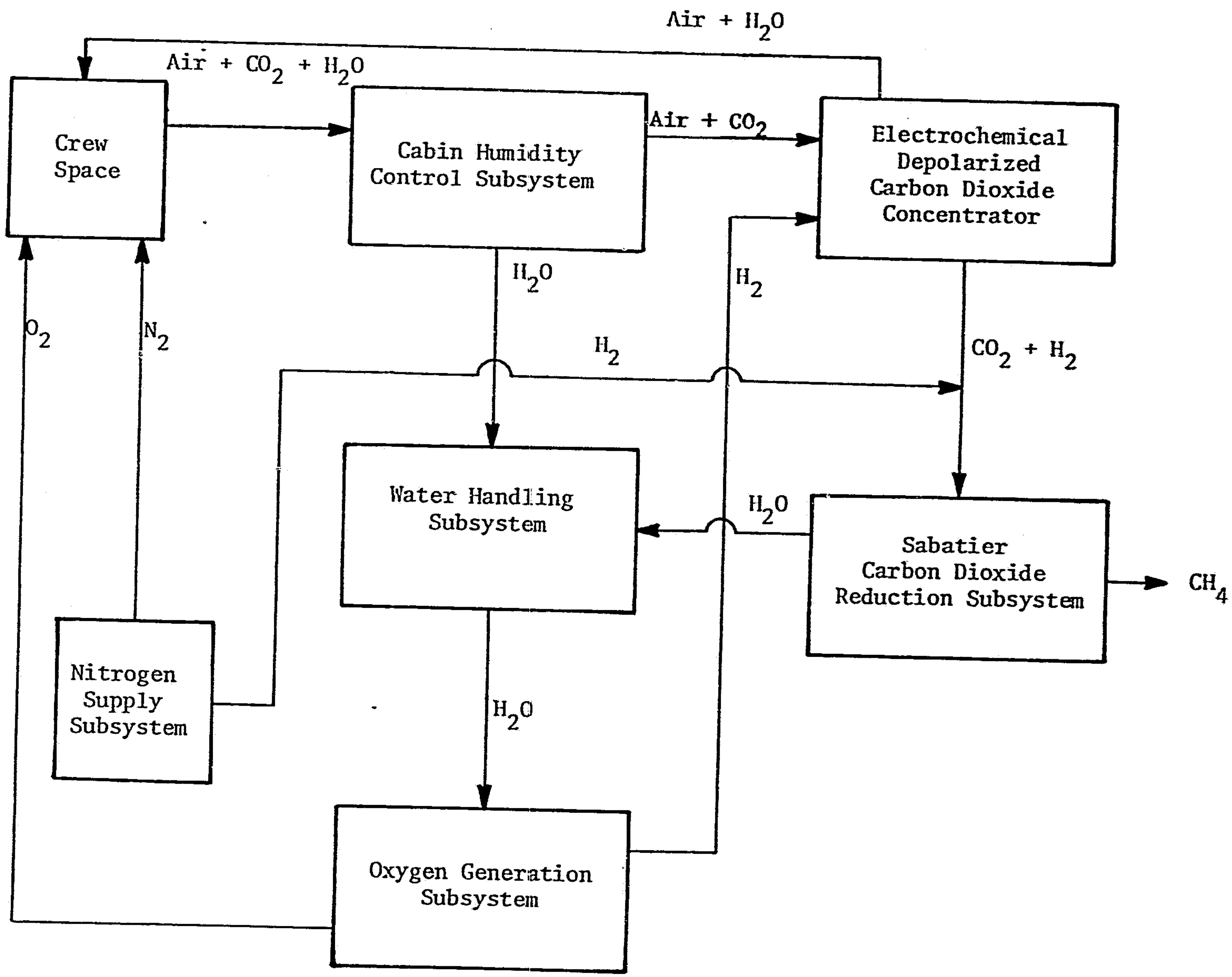


FIGURE 11 AIR REVITALIZATION SYSTEM BLOCK DIAGRAM

TABLE 5 ONE-PERSON AIR REVITALIZATION SYSTEM DESIGN REQUIREMENTS

Crew Size	1
Carbon Dioxide Removal Rate, kg/d (lb/d)	1.00 (2.20)
Oxygen Generation Rate, kg/d (lb/d)	1.03 (2.27)[a]
Water Vapor Removal Rate, kg/d (lb/d)	1.80 (3.96)
Liquid Water Production Rate, kg/d (lb/d)	1.49 (3.27)
Methane Production Rate, kg/d (lb/d)	0.36 (0.79)
Nitrogen Production Rate, kg/d (lb/d)	0.60 (1.32)

(a) Consists of 0.84 kg/d (1.84 lb/d) oxygen metabolic and 0.19 kg/d (0.43 lb/d) for leakage and EDC requirements.

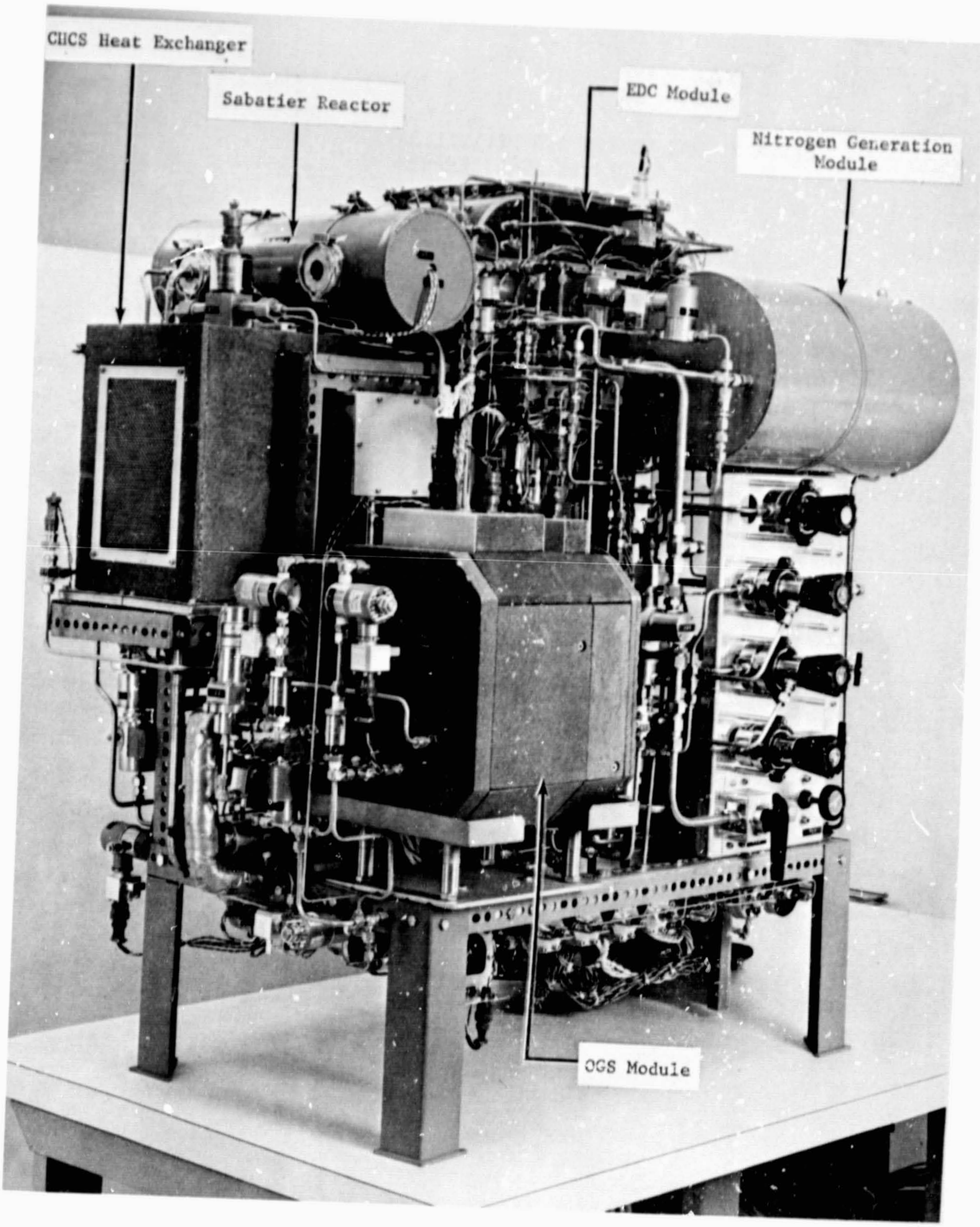


FIGURE 12 ARX-1 MECHANICAL HARDWARE

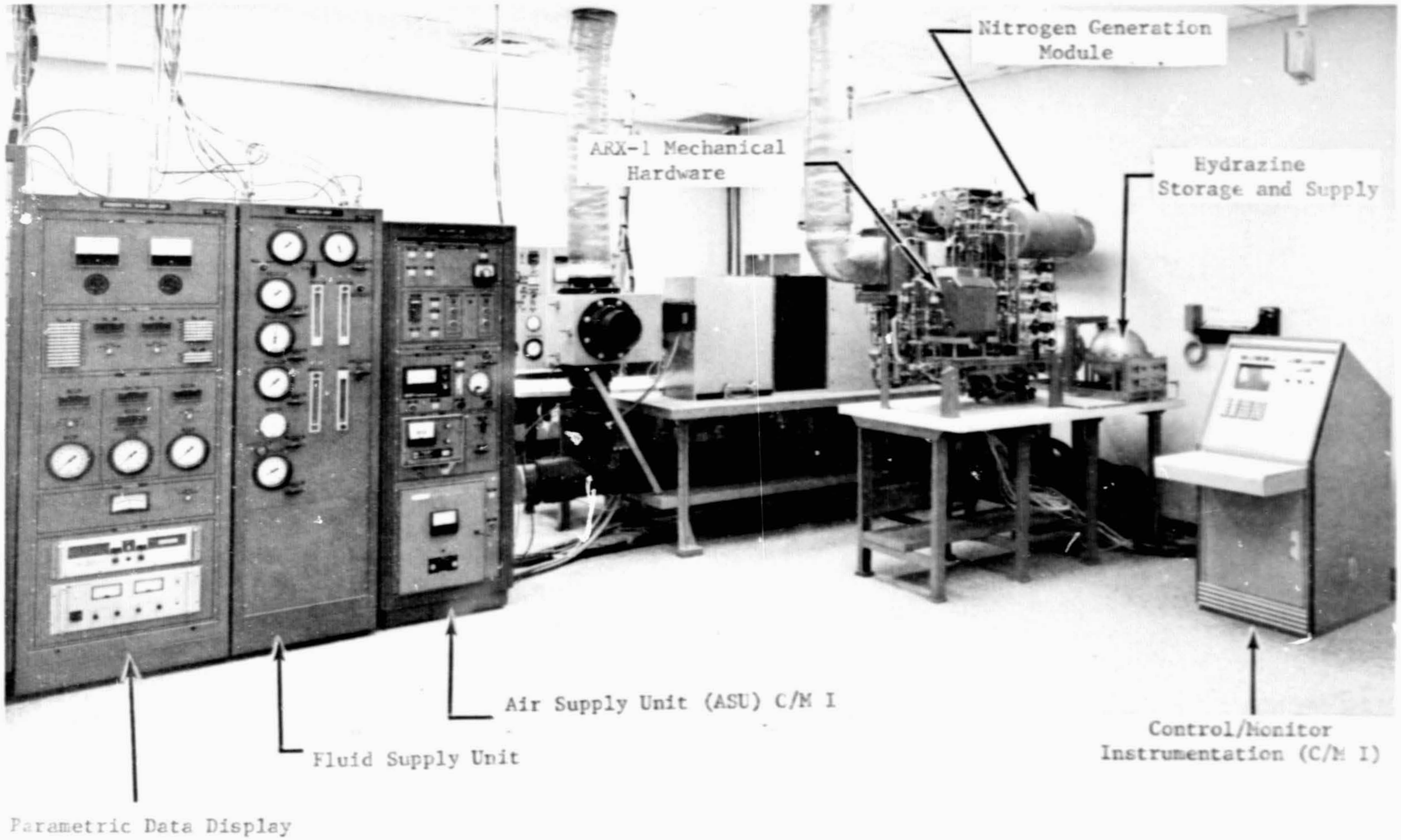


FIGURE 13 ARX-1 TEST FACILITY

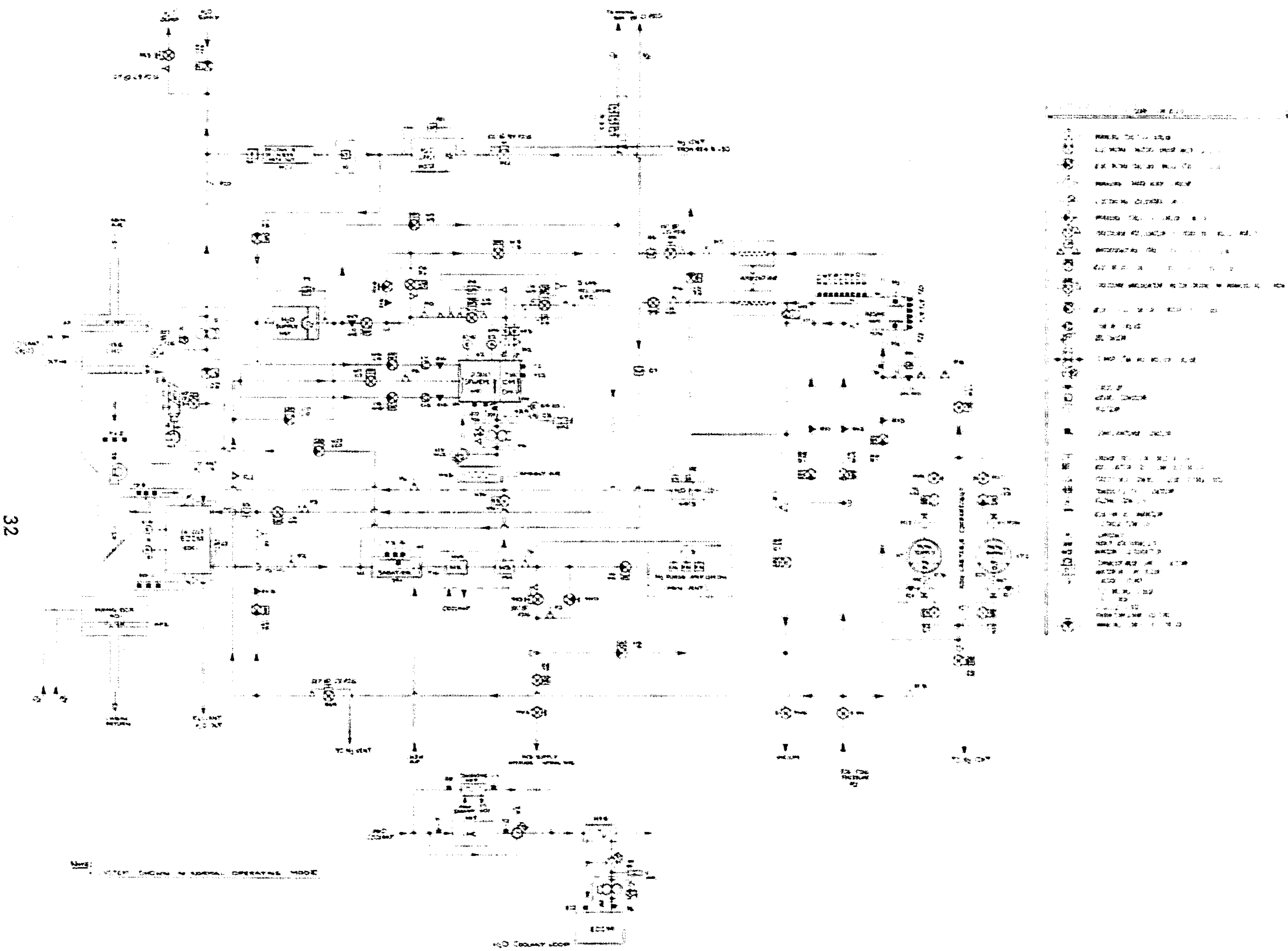
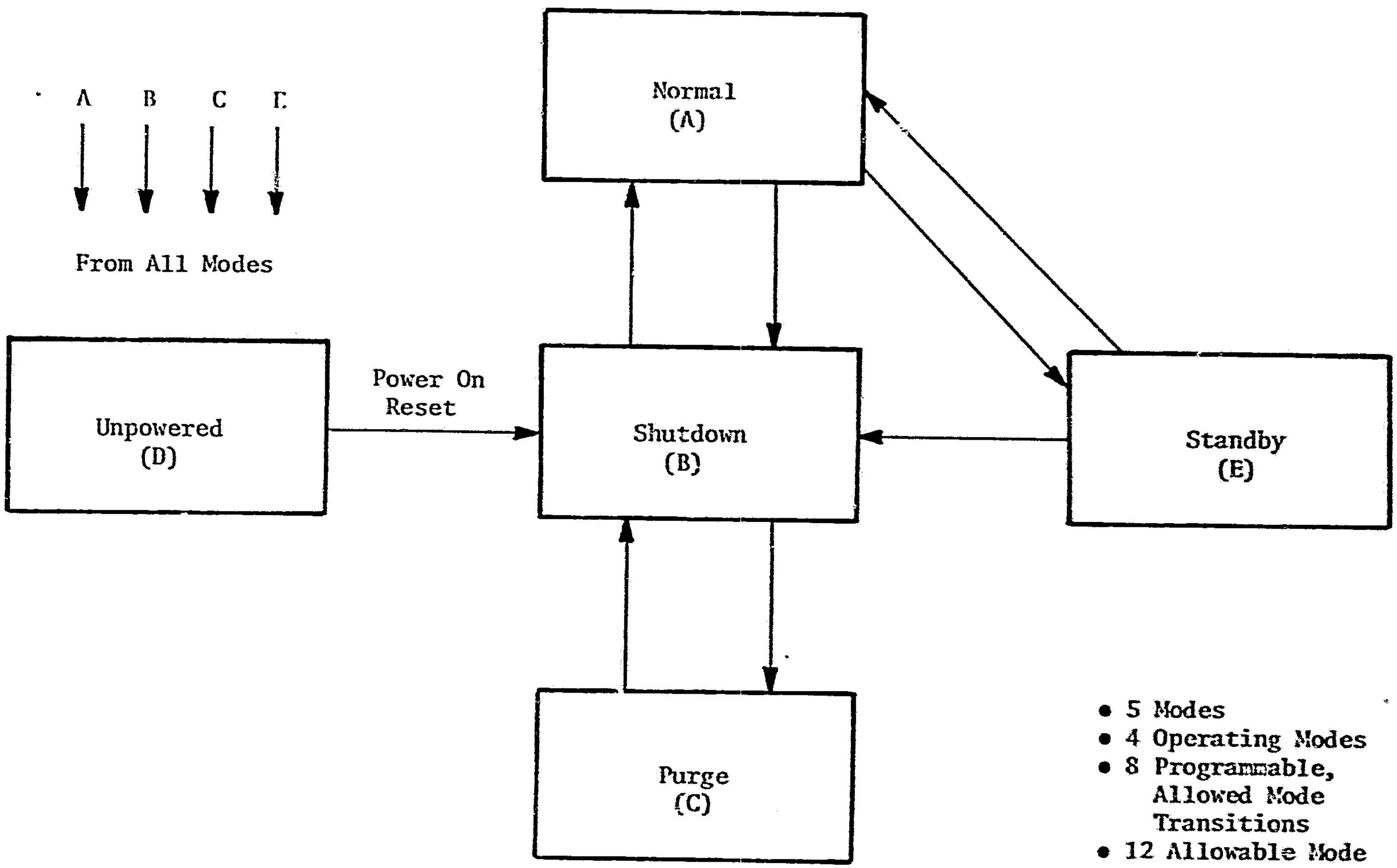


FIGURE 14 ARX-1 MECHANICAL SCHEMATIC

FIGURE 15 ARX-1 CONTROL AND MONITOR INSTRUMENTATION



- 5 Modes
- 4 Operating Modes
- 8 Programmable, Allowed Mode Transitions
- 12 Allowable Mode Transitions

FIGURE 16 OPERATING MODES AND ALLOWABLE MODE TRANSITIONS

however, all modes can transition to the unpowered mode during which time all actuators and valves will go to the de-energized position. Upon repowering the ARX-1 all actuators are put in the shutdown position.

System Control and Monitoring. There are 16 software-implemented controls needed to operate the ARX-1. These include controls for EDCM temperature and current, S-CRS temperature, CHCS temperature, water accumulator fill and/or empty, OGS temperature, pressure and current, NGM pressure and temperature. The four software controls for the NSS are highlighted in Table 6. These are active during the operating modes or the mode transitions. The NSS actuator conditions for the four operating modes are given in Table 7.

Sensors are required to interface with the C/M I to provide for control and monitoring of subsystem parameters and performance. Over 100 sensors are implemented in the ARX-1. These monitor flows, pressures, temperatures, currents, voltages, liquid levels, combustible gas presence and valve positions. Thirty-three sensors, identified in Table 8, are specifically associated with the NSS. Table 8 also identifies subsystem parameter conditions which will call for an automatic, controlled shutdown of the ARX-1. The shutdown conditions can be easily modified by the operator through an operator/system interface.

Operator/System Interface. Figure 17 shows the operator/system interface panel of the C/M I through which the operator can communicate with the system. The panel is subdivided into three major areas: System Status, Operator Commands and System Control.

The overall system status is provided in the upper left-hand portion of the panel. The status summary is given as Normal, Caution, Warning or Alarm and is determined by the worst case condition for any critical parameter. A reset button is provided to clear the status summary and reset the subsystem monitoring functions. Messages and information concerning the system are displayed on a Cathode-Ray Tube (CRT) located below the status summary indicators. In addition, the CRT displays fault diagnostic messages, present status and values of selected sensors, input/output data, elapsed times and communications between the system and an operator.

The "Operator Commands" section in the lower left-hand corner provides the capability of the operator to communicate with the system. Capability exists for entering data, examining current values, updating scale factors, modifying setpoints or allowable ranges and control of the CRT display.

Manual initiation of the four operating modes (Normal, Shutdown, Purge and Standby) is provided in the upper right-hand corner of the panel. The controls automatically prevent the operator from initiating an illegal mode transition (e.g., Normal to Purge). The subsystem will not respond to an illegal mode transition command. Accidental mode initiation is prevented by providing a mode change permit button which must be simultaneously depressed with the desired mode button.

The control status is located directly below the operating mode/commands section. Two lights are provided to indicate whether one of the automatic protection overrides or an actuator override has been activated. A light is

TABLE 6 NSS/ARX-1 CONTROLS DEFINITION

Control	Description	Sensor(s)	Actuator(s)	Software Program(s)	Control Setpoint
NGM Operating Pressure	Sets the operating pressure and controls of the N_2H_4 storage tank and feed pressure to the desired setpoint	P18, P23	V27,V30,V31	NGMPRS, PCL	P18, P23- 1790 kPa (260 psia)
NGM Dissociator Temperature	Controls NGM Dissociator Temp. (T24) to desired setpoint by actuating heater H2. Maintains heater temperature (T23) at desired setpoint	T23,T24	H2	NGMPRO,TCL	T23- 1085 K (1475 F) T24- 1020 K (1375 F)
NGM Pd/Ag Temperature	Controls NGM Separator Temperature (T28) to desired setpoint by actuating heater H3. Maintains heater temperature (T30) at desired setpoint.	T28,T30	H3	NGMTP1,TCL	T28- 640 K (700 F) T30- 700 K (800 F)
N_2H_4 Feed	Selects one N_2H_4 storage tank for use. Switches to other tank when first is empty and alerts operator to refill empty tank.	P24,P25	V32-V35	N2H4FD	

TABLE 7 ACTUATOR CONDITIONS FOR NSS/ARX-1 OPERATING MODES

Actuator[(a)]	Function	Operating Mode			
		Shutdown	Normal	Standby	Purge
V24	Hydrogen Product Purge	O[(b)]	O	O	O
V25	Nitrogen Product Purge	O	C	C	O
V26	Hydrogen to Vacuum	C	O	O	C
V27	Hydrazine Feed	C	O	C	C
V28	Hydrogen Product Purge	C	C	C	O
V29	Hydrogen Vacuum Purge	C	C	C	O
V30	NGM Pressure Control Regulator	C	O[(c)]	O[(c)]	O[(c)]
V31	Nitrogen Product Purge, NGM Pressurization	C	C	C	O
V32	Tank A Outlet	C	(d)	(d)	C
V33	Tank B Outlet	C	(d)	(d)	C
V34	Tank A Inlet	C	(d)	(d)	C
V35	Tank B Inlet	C	(d)	(d)	C
V37	Hydrogen Product Vacuum	O	C	C	O
H2	Dissociator Heater	Off	On[(c)]	On[(c)]	Off
H3	Separator Heater	Off	On[(c)]	On[(c)]	Off

(a) See Figure 14 for actuator location.
(b) O indicates actuator open, C indicates actuator closed.
(c) Under software control.
(d) Condition depends on which hydrazine tank is used.

TABLE 8 NSS/ARX-1 SENSOR LIST

Sensor[a]	Parameter Monitored	Nominal Value[b]	Shutdown Points[b] Low	Shutdown Points[b] High
P15	Nitrogen Outlet Pressure	1720 (250)	1590 (230)	1830 (265)
P16	Hydrogen Outlet Pressure	103 (15)	-	280 (40)
P17	Hydrogen Vacuum Pressure	0.7 (0.1)	-	28 (4)
P18	Hydrazine Feed Pressure	1790 (260)	1690 (245)	2000 (290)
P19	Nitrogen Supply Pressure	2070 (300)	1790 (260)	2340 (340)
P23	NGM Purge & Tank Source Pressure	1790 (260)	1690 (245)	2070 (300)
P24	Tank A Nitrogen Pressure	1790 (260)	1690 (245)	2070 (300)
P25	Tank B Nitrogen Pressure	1790 (260)	1690 (245)	2070 (300)
T23	Dissociator Heater Control Temperature	1075 (1475)	980 (1300)	1090 (1500)
T24	Dissociator Control Temp.	1020 (1375)	870 (1100)	1090 (1500)
T25,T26	Dissociator Temperature	1020 (1375)	870 (1100)	1090 (1500)
T27,T29	Separator Temperature	640 (700)	590 (600)	700 (800)
T28	Separator Control Temp.	640 (700)	590 (600)	700 (800)
T30	Separator Heater Control Temperature	700 (800)	640 (700)	760 (900)
T31	Hydrazine Feed Temperature	297 (75)	-	305 (90)
Q5	Nitrogen Product Flow Rate	2200	-	3500
Q7	Hydrogen Product Flow Rate	3680	-	5000
Q8	Hydrazine Feed Flow Rate	2.85	1.00	4.73
W24-W35, W37	Valve Position Indicator	Valve Position	-	-

(a) See Figure 14 for sensor location.
(b) Pressure given in kPa (psia), temperature in K (F) and flow rate in cm^3/min.

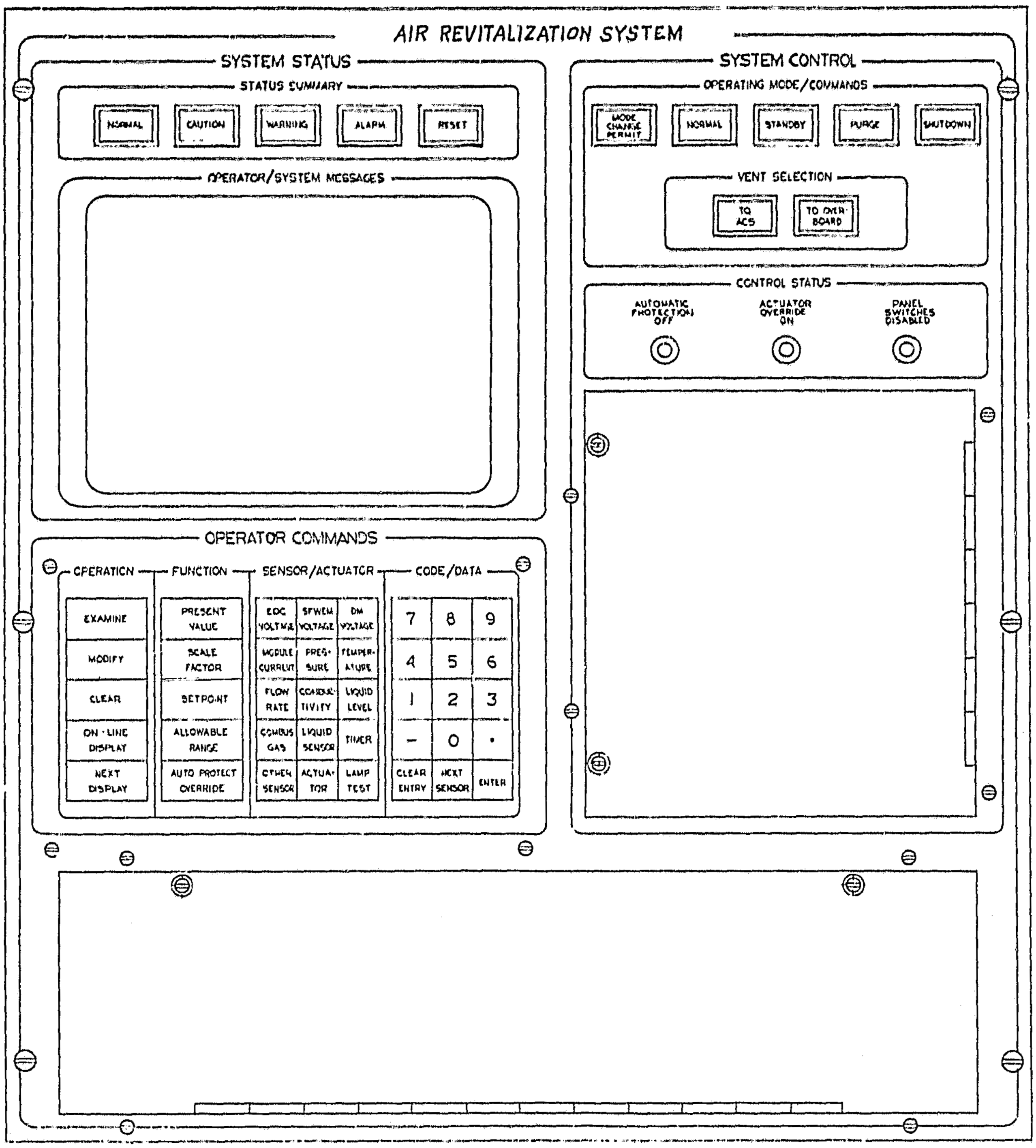


FIGURE 17 ONE-PERSON AIR REVITALIZATION SYSTEM OPERATOR/SYSTEM INTERFACE PANEL

also provided to indicate when the panel switches have been disabled in order to prevent unauthorized personnel from activating any button.

Manual controls, desired primarily for use during system debug or off-design operation, are provided behind an access panel located immediately below the operator commands and system control sections. Overrides are provided for all actuators in the form of toggle switches. The actuator overrides are placed in an automatic position for the system to operate normally. The access panel is normally closed to prevent accidental actuations.

Software

The ARX-1 software is organized into 70 different software packages or modules. They are divided into system definition and data base, front panel service, real-time executive, input/output, control/monitor, operating mode control and intermode transition functions. Of the total, the NSS requires six of the modules exclusively and share the majority of the remainder.

Test Support Accessories

Test Support Accessories were developed to support the test program of the NSS/ARX-1. A block diagram of the overall ARX-1 TSA is shown in Figure 18. Some of the TSA hardware was developed or refurbished as part of this program; some was provided from prior programs and modified. Test Support Accessories that were needed specifically for the NSS testing included the vent/vacuum source, N_2 high pressure supply, N_2H_4 refill and supply and provisions for parametric data display and analysis.

Figure 19 shows the NSS TSA schematic required for operation. The primary function of the TSA is to supply N_2H_4 to the storage tanks located in the NSS and shown in Figure 20. These storage tanks are N_2 pressurized bladder tanks suitable for zero-g operation. Bulk N_2H_4 is stored in a 0.21 m^3 (55 gal) drum which cannot be pressurized over 138 kPa (20 psia). In order to transfer the N_2H_4 from the drum located in the N_2H_4 storage area to the tanks located in the NSS requires greater than 138 kPa (20 psia). An intermediate higher pressure transfer tank is used for this purpose. After refilling the NSS N_2H_4 tanks, the line connecting the transfer tank which is located near the storage drum and the TSA located at the NSS/ARX-1 is purged with N_2 to remove any N_2H_4 in the lines as a safety precaution. In addition to N_2H_4 tank refilling components, the TSA supplies purge N_2 and distributes the purge N_2 for use in other ARS subsystems.

Parametric data display provisions included real-time strip chart recording of selected NSS sensors. Two recorders were used. One recorder monitored N_2H_4 feed flow rate, feed pressure and dissociator temperature. The other was a temperature recorder which monitored eight experimental thermocouples installed in the NGM. These were in addition to those monitored by the C/M I. A gas chromatograph was used to periodically sample the product N_2 stream and measure the N_2, H_2 and NH_3 concentrations.

NSS/ARX-1 Test Program

The test program consisted of several subsystem and integrated system checkout

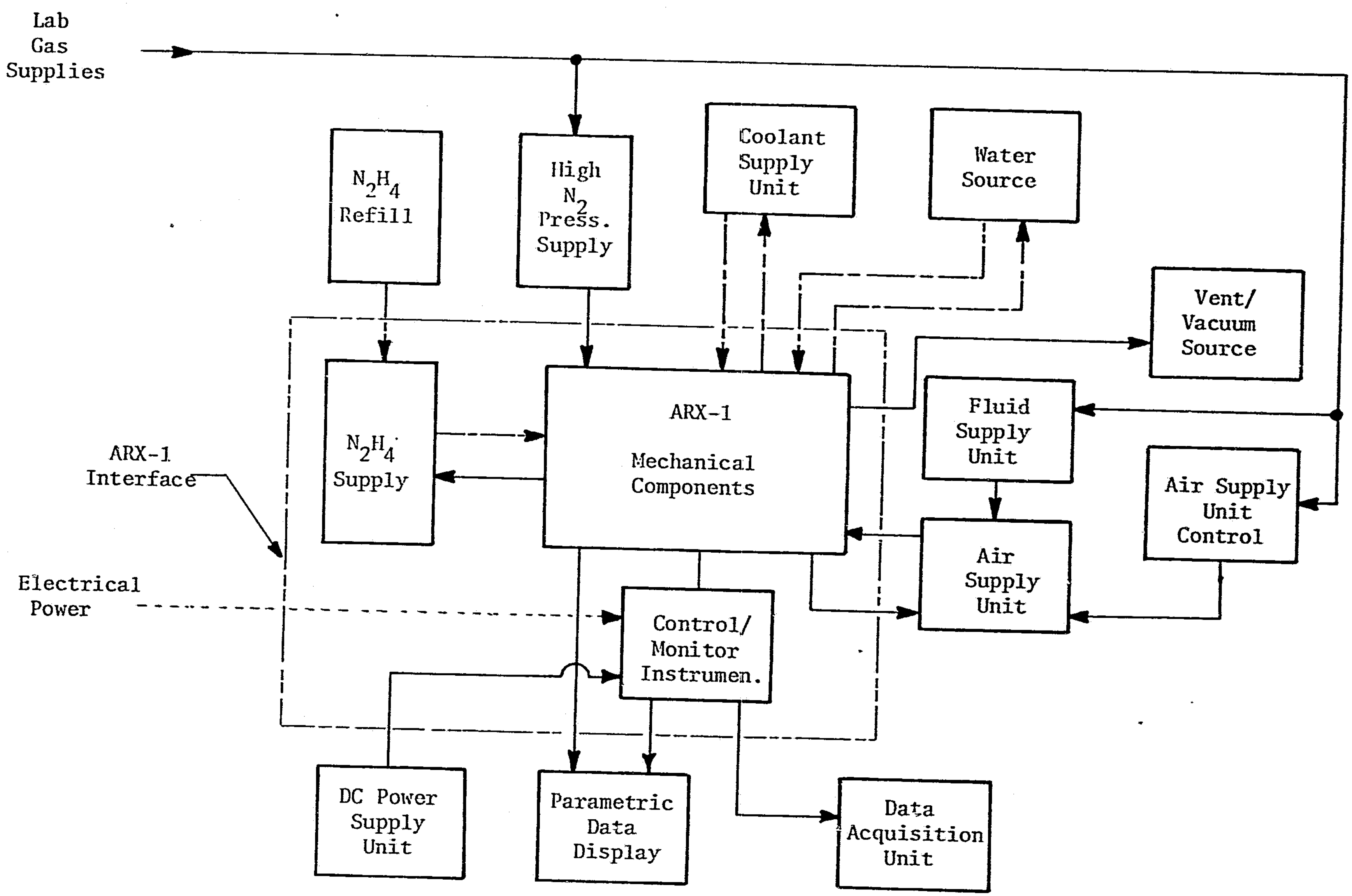


FIGURE 18 ONE-PERSON AIR REVITALIZATION SYSTEM TSA BLOCK DIAGRAM

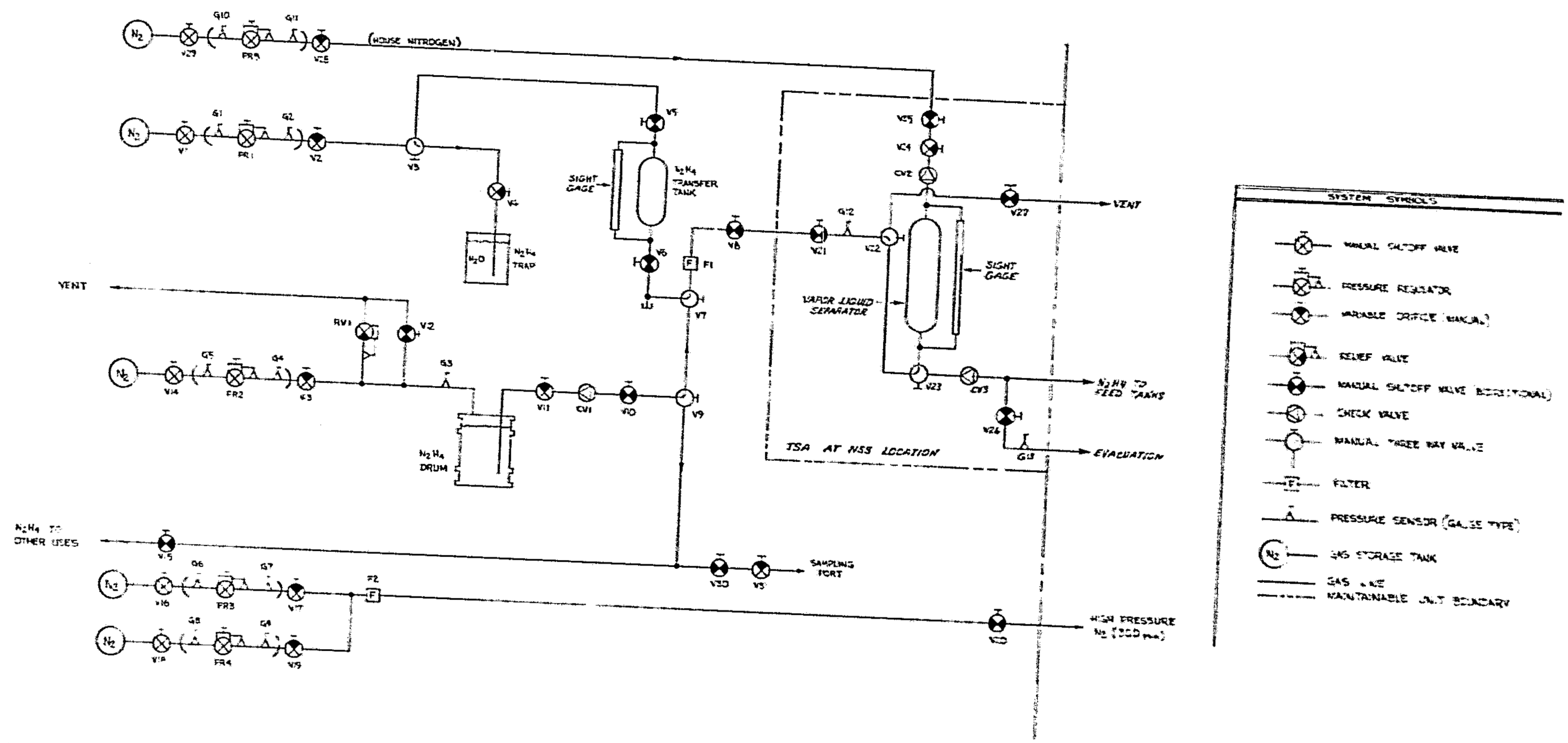


FIGURE 19 NSS TEST SUPPORT ACCESSORIES

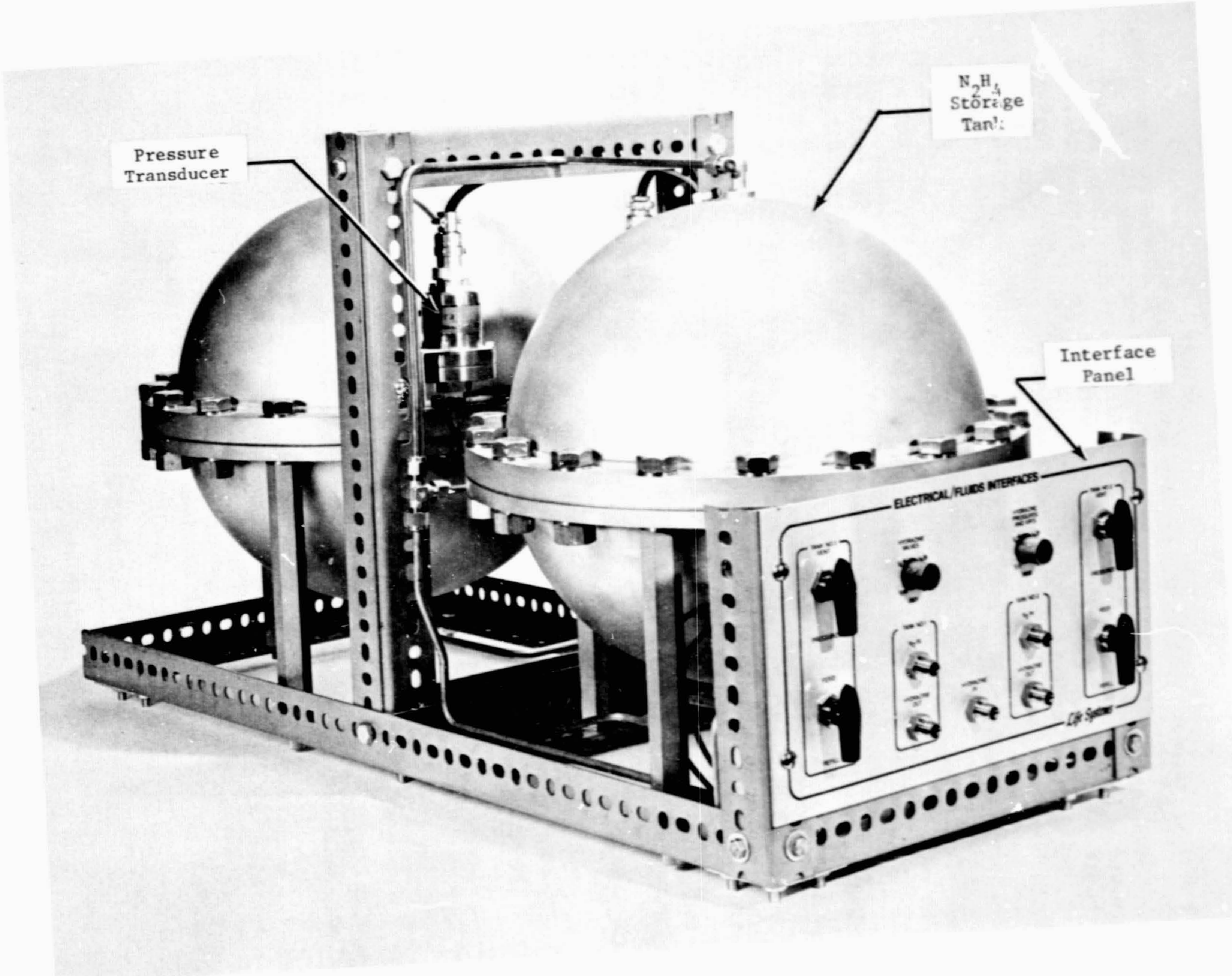


FIGURE 20 HYDRAZINE STORAGE AND FEED ASSEMBLY

and operational tests to verify NSS/ARX-1 integrated design and operation and NGM performance.

Over 50 days of various types of testing was accomplished. These are summarized in Table 9. The majority of the testing time involved the integration of the mechanical NSS and TSA hardware with the ARX-1 C/M I software. Minor modifications to the software were made to accommodate differences between as-designed and as-built configurations. Principally, the mode sequences and NSS control routines needed to be modified to accommodate needed changes in operating philosophy and knowledge gained as the testing evolved. The final system configuration demonstrated single button startup and automatic control and monitor at normal conditions.

Shakedown testing and operation at the nominal design point as well as operation with varying conditions of the integrated system were successfully completed. The operating conditions and test results are shown in Table 10. The product N_2 composition, as measured by the gas chromatograph verified the effectiveness of the staging concept used in the NGM.

The efficiencies calculated from the test results are comparable with those projected for the NGM design. However, the very low NH_3 concentration desired was not achieved due to internal leakage in the separator stages. A post-test examination and analysis of the NGM revealed a design weakness in the separator housing. The bolt-down flanges of the housing showed signs of high temperature material yield and structural deformation which led to seal leakage. A design modification has been identified and would be implemented prior to any future testing.

MINI-PRODUCT ASSURANCE PROGRAM

The mini-Product Assurance Program established, implemented and maintained throughout the development of the NSS included considerations for quality assurance, reliability, maintainability, safety, materials control and configuration management. The following sections summarize the activities completed in each area.

Quality Assurance Program

The objective of the Quality Assurance Program was to search out quality weaknesses and provide appropriate corrective actions. Quality assurance considerations were included during the NSS design, engineering evaluation and fabrication activities. All vendor-supplied parts were checked out when received to ensure adherance to design specifications prior to assembly into the NSS. Only minor quality deficiencies in vendor-supplied parts were identified during the program and all were resolved prior to incorporation into the NSS.

Reliability Program

The objective of the Reliability Program was to include reliability considerations into the design of the NSS. Redundant shutoff valves and dual zero-g compatible N_2H_4 storage tanks were incorporated into the NSS design. A review of literature for projected N_2H_4 storage and handling techniques resulted in

TABLE 9 NSS/ARX-1 TEST SUMMARY

Test Element	Type of Test	Test Duration, d
NGM	Pd/Ag Tube Braze Integrity	3
	Module Pressurization	1
NSS	Pressure, Temperature and Flow Sensor Calibration	4
	Plumbing Integrity	1
	Valve Sequencing	2
TSA	Hydrazine Tank Pressure Integrity	3
	Tank Filling Time	2
	Hydrazine Transfer Line Operation	4
	Recorder Checkout	1
C/M I	Tank Pressurization	3
	Tank Selection	4
	Dissociator Temperature Control	2
	Separator Temperature Control	2
	Purge Control	1
	Mode Transition Sequences	10
Integrated System	Startup/Shutdown Checkout	8
	Shakedown Test/Nominal Condition	5
	Shakedown Test/Varying Conditions	3

TABLE 10 SHAKEDOWN TEST RESULTS

<u>Operating Conditions</u>	
Hydrazine Feed	
Flow Rate, cm^3/min	1.80
Pressure, kPa (psia)	1790 (260)
Product Nitrogen Outlet Pressure, kPa (psia)	1720 (250)
Product Hydrogen Outlet Pressure, kPa (psia)	98.6 (14.3)
Dissociator Temperature, K (F)	890 (1142)
Separator Temperature, K (F)	629 (673)
<u>Test Results</u>	
Product Nitrogen Flow Rate, cm^3/min (cfm)	1760 (0.062)
Product Hydrogen Flow Rate, cm^3/min (cfm)	2280 (0.080)
Product Nitrogen Composition, %	
Nitrogen	99.154
Hydrogen	0.502
Ammonia	0.344

the selection of locating the N_2H_4 storage tanks in the nonhabitable compartment section of the spacecraft. All liquid N_2H_4-carrying lines were then considered nonmaintainable and required redundant valving to meet reliability requirements.

Maintainability Program

The objective of the Maintainability Program was to consider "hands off" operation as a design goal and routine maintenance required during testing. A line replaceable or flight replaceable component concept was selected to maintain those components requiring maintenance to achieve the desired subsystem reliability goal during any continuous 180-day operational period. All subsystem components, with the exception of those located in the liquid N_2H_4 lines, were considered line replaceable components.

Safety Program

An effort was made during the design of the NSS to consider if operation of the subsystem is consistent with flight safety requirements. All N_2H_4 handling requirements and safety considerations as established during previous programs were reviewed, upgraded and implemented during the present NSS development. In addition to the N_2H_4 safety requirements, the following safety features were also incorporated:

1. A single failure in one component did not cause successive failures in other components.
2. The subsystem was designed so that operation and maintenance can be performed without hazard to personnel.
3. As a safety precaution against the possibility of external leakage of N_2H_4 and H_2 from all N_2H_4 or H_2-carrying lines, the design used welded plumbing wherever feasible.
4. Provisions have been made so that circuit breakers are incorporated (in TSA) to protect electrical equipment from unexpected high currents.
5. Electrical connectors, plugs and receptacles are positively keyed to prevent incorrect mating with other accessible connectors, plugs or receptacles.
6. In all connections, the hot electrical connector was the female socket.
7. Electrical circuits are not routed through adjacent pins of an electrical connector if a short between them will constitute a failure which could cause a serious problem.
8. The fluid and electrical interface panel were clearly labeled to prevent incorrect connection of fluid and electrical lines.

Materials Control Program

The objective of the Materials Control Program was to provide assurance that the NSS would not preclude the efficient application of a more detailed subsystem

material control program during follow-on efforts. Special consideration was given to compatibility with N_2H_4. All metallic and nonmetallic materials used in N_2H_4-carrying lines were screened for compatibility and were only accepted if they met all compatibility criteria. All metallic and nonmetallic materials selected were compatible with their environment and scheduled maintenance was not selected as a method of working around possible corrosion or materials compatibility problems.

Configuration Management Program

The objective of the Configuration Management Program was to ensure that the NSS was integratable as part of a central ARS. Activities in this area were limited to supplying NSS interface requirements and reviewing interface requirements of other central ARS subsystems.

TECHNOLOGY ADVANCEMENT STUDIES

As part of the contractual effort, two studies directed toward the advancement of the NSS technology were completed. The first supported the development of the improved sealing technique for the NGM while the second evaluated the NSS test philosophy as operated with the ARX-1.

NGM Sealing Improvements

Prior development activities had shown unsatisfactory performance of the graphite gaskets used to seal the NGM metal surfaces. Specifically, cold flowing of the gaskets under compression and fracturing of the gaskets upon disassembly made them nonreusable. The use of different gasket materials was investigated and new seals were selected for the NGM development. These new seals were subjected to several tests to determine their sealing characteristics prior to incorporation into the design. The following summarizes the tests and findings.

The new seals consisted of flange-backed graphite gaskets. Figure 21 is a functional schematic of the new sealing technique. Graphite gaskets are retained on both sides of an S-type metal flange. The flange acts like a spring to maintain a constant sealing force as the two metal surfaces are drawn together. The metal-flange grooves also provide support for the gasket material so it does not disintegrate under high pressures and temperatures. The graphite gaskets are compressed on both sides of the flange to provide good sealing.

Sample Gasket and Test Setup

Six sample gaskets were procured and used for seal checkout testing to verify the new sealing concept. These had dimensions of 19.3 cm (7.6 in) ID and 20.8 cm (8.2 in) OD to simulate closely the configuration of the required NGM seals. Two different materials were evaluated - SS321 and cold rolled steel. Three different flange metal thicknesses were chosen - 0.381, 0.254 and 0.127 mm (0.015, 0.01 and 0.005 in).

A seal test fixture was designed and fabricated to enable quick and simple installation, test and removal. The fixture consisted of two bolted steel

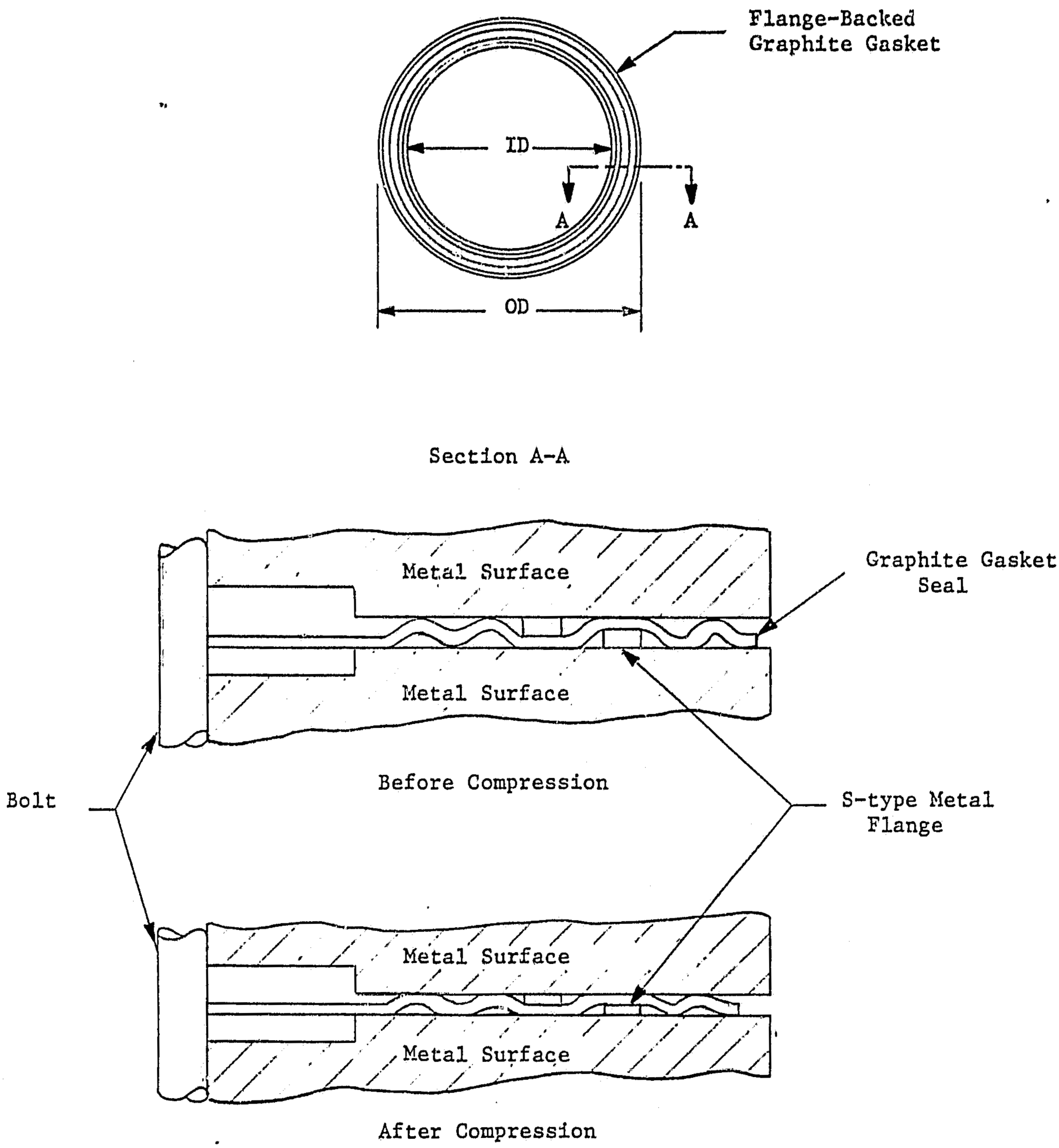


FIGURE 21 FUNCTIONAL SCHEMATIC OF THE NEW SEALING CONCEPT

plates, compressing the sample gasket which surrounded a small pressurized reservoir. A simple test setup consisted of a pressure source (N_2), pressure gauge and hand valves. The test fixture was installed in an oven to maintain the desired test temperatures.

Seal Tests

The seal testing consisted of three major groups: (1) cold test, (2) hot test and (3) thermal cycle testing. The objective of the cold test was to measure the leakage rate at high pressures (up to 3550 kPa (500 psig) and ambient temperature. The hot test consisted of leakage rate measurements at high pressures and temperatures (700-733 K) (800-860 F)). The objective of the thermal cycling test was to evaluate the sealing capability of the new seals through repeated thermal cycles (hot-cold-hot-cold) for an extended period of testing.

Results of the cold test are presented in Table 11. The test fixture was pressurized with N_2 and the leak rate through the seal to ambient air was measured at ambient temperature. Pressure drops were measured as a function of time and were converted to the volumetric leak rate using the following equation:

$$L_v = \frac{51.48}{T} \left(\frac{\Delta P}{\Delta T}\right) \tag{4}$$

where L_v = volumetric leak rate per unit length of seal under standard conditions (294 K (70 F) and 101 kPa (14.7 psia)), $dm^3/min/cm$

T = absolute temperature, R

and $\Delta P/\Delta T$ = pressure drop per unit time, psi/min

The leakage rates shown in Table 11 are essentially negligible. As a comparison, a leakage rate of 1×10^{-5} $dm^3/min/cm$ (2.4×10^{-4} $in^3/min/in$) when referenced to the NGM at normal operation is about 0.02% of the total flow rate.

Following the cold test, the test fixture was placed in an oven and heated above 700 K (800 F). The seal held exceptionally well with a leak rate of 1.2×10^{-6} $dm^3/min/cm$ (2.8×10^{-5} $in^3/min/in$) at 2520 kPa (365 psia).

The thermal cycle testing involved leakage rate measurements made during repeated thermal cycles. Typical thermal cycling shown in Figure 22. After taking a pressure reading the test fixture was cooled to approximately 320 K (116 F) and heated back to 720 K (836 F). Pressure was then adjusted to 2520 kPa (365 psia). These settings of pressure and temperature were selected with safety considerations relative to nominal NGM operating conditions of 1720 kPa (250 psia) and 644 K (700 F). Pressure drop measurements were made over a 15-hour period. Results of the thermal cycle testing are presented in Table 12. The seal performed better as time passed. After test No. 25, the leak rate remained virtually zero (less than 8×10^{-8} $dm^3/min/cm$ (2×10^{-6} $in^3/min/in$)).

TABLE 11 SEAL COLD TEST RESULTS

Seal[a]	Pressure, kPa (psia)	Leakage Rate,[b] $dm^3/min/cm$, x 10^6 ($in^3/min/in$, x 10^4)
1	3550 (515)	243 (58.4)
1	3380 (490)	117 (28.1)
1	3210 (465)	58 (14)
1	2860 (415)	39 (9.4)
2	3550 (515)	49 (12)
2	3210 (465)	73 (18)
2	2520 (365)	0.16 (0.038)
3	2860 (415)	21 (5.0)
3	2790 (405)	17 (4.1)
3	2760 (400)	9.6 (2.3)
3	2720 (395)	6.7 (1.6)
3	2690 (390)	6.7 (1.6)

(a) Seal Identification (Flange Support):
1 - 0.381 mm (0.015 in), SS321
2 - 0.254 mm (0.01 in), Cold Rolled Steel
3 - 0.127 mm (0.005 in), SS321

(b) Volumetric leakage rate per unit length of seal under standard conditions.

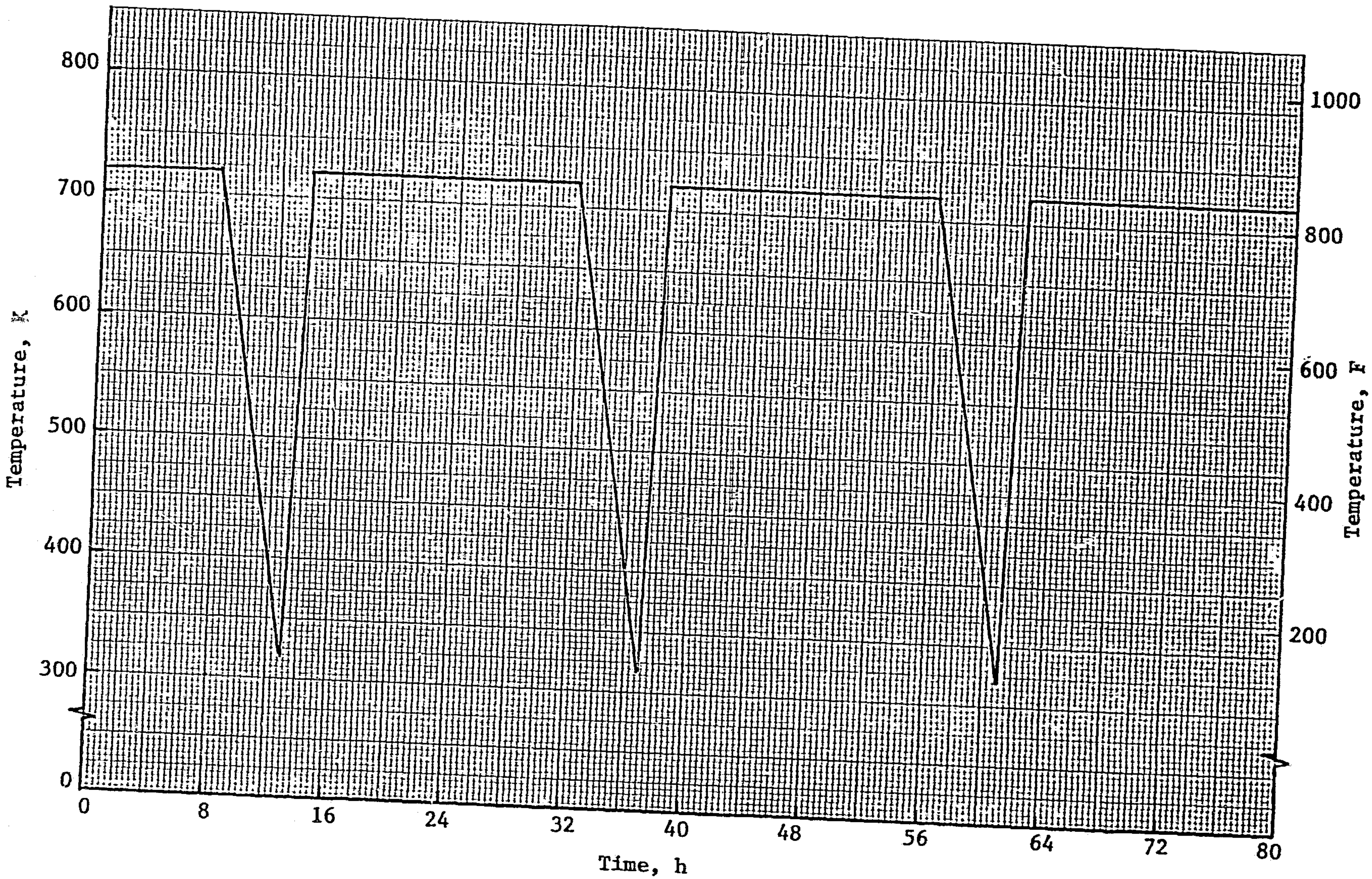


FIGURE 22 THERMAL CYCLE PROFILE FOR SEAL TESTS

TABLE 12 SEAL THERMAL CYCLE TESTING RESULTS

Test No.[a]	Temperature, K (F)	Leakage Rate,[b] $dm^3/min/cm$, x 10^6 ($in^3/min/in$, x 10^5)
1	722 (840)	1.3 (3.1)
2	711 (820)	0.93 (2.2)
3	711 (820)	0.80 (1.9)
4	709 (816)	0.89 (2.1)
5	712 (822)	0.92 (2.2)
6	706 (811)	0.85 (2.0)
7	701 (802)	1.1 (2.6)
8	707 (814)	0.81 (1.9)
9	712 (822)	0.88 (2.1)
10	717 (832)	0.52 (1.2)
11	719 (834)	0.83 (2.0)
12	725 (845)	1.0 (2.4)
13	707 (814)	1.0 (2.4)
14	731 (856)	0.0 (0)
15	714 (825)	0.08 (0.19)
16	717 (831)	0.04 (0.096)
17	712 (822)	0.02 (0.048)
18	719 (834)	0.08 (0.19)
19	717 (832)	0.08 (0.19)
20	714 (825)	0.08 (0.19)
21	711 (820)	0.08 (0.19)
22	719 (834)	0.08 (0.19)
23	732 (859)	0.0 (0)
24	719 (834)	0.02 (0.048)
25	719 (834)	0.04 (0.096)

(a) Using seal with 0.254 mm (0.01 in) thick flange support.
(b) Volumetric leak rate per unit length of seal under standard conditions.

The sealing test demonstrated that both leakage rate and structural integrity of the new seals was acceptable for the NGM application. Gaskets using the flanged-backed concept were procured for the shakedown tests described in a previous section.

NSS/ARX-1 Testing Philosophy

While the ARX-1 was designed for operation at the one-person level, the NSS was sized to generate N_2 at an equivalent six-person capacity. Therefore, a solution associated with handling excess N_2 and H_2 for integrated operation of the NSS with the ARX-1 was required. Three alternatives were evaluated:

1. Operate the NSS at the six-person level and bleed off excess N_2 and H_2.

2. Operate the NSS one-sixth of the time in the Normal Mode (six-person level) and the remaining time in the Standby Mode.

3. Operate the NSS at the one-person level.

All three optional methods were technically feasible, but the second option required costly modifications associated with storing excess N_2 and H_2 and additional flow controls to maintain constant flows of these gases. Accordingly, that option was not recommended. The third option was a simple solution since it involved only modification of control setpoints of process parameters. No technical problems were expected for operation of NH_3 dissociators and N_2/H_2 separators. However, some difficulties were expected in the operation of the N_2H_4 cracker, since the boiling zone may shift from that of the original design.

The first option was simple in concept and involved only minor plumbing changes to bleed off excess product gases. Therefore, it was selected for the testing of the NSS within the ARX-1. As it happened, when the NSS underwent testing, the other ARX-1 subsystems were not scheduled to be operated and the impact of different person-level operation was obviated.

CONCLUSIONS

The following conclusions were reached as a result of the program activities:

1. The integration of multiple H_2 separation, and N_2H_4 and NH_3 dissociation stages into the NGM is feasible. The design completed successfully integrated eight dissociation/separation stages into a single package to effectively use the heat generated in the N_2H_4 dissociation process to heat the other stages.

2. The NGM staging technique is an effective method of delivering high purity N_2 for spacecraft leakage makeup. Data gathered on an NH_3 dissociation stage verified that low NH_3 concentrations are attainable using the NGM.

3. The NSS was designed, integrated and operated as part of a central ARS. The NSS was sized to deliver 3.64 kg/d (8.00 lb/d) of N_2 at greater than or equal to 1725 kPa (250 psia). This N_2 generation rate corresponds to a six-person spacecraft application.

4. The improved NGM sealing technique using flanged-backed graphite gaskets does provide reproducible bubble-tight seals required for future testing.

5. The NGM separator housing flanges require a design modification to prevent high temperature material yield and deformation.

RECOMMENDATIONS

The following recommendations are a direct result of the work completed:

1. The NSS should be extensively tested as an integratable subsystem within the central ARS as developed under this program to determine its performance as a function of N_2H_4 feed rates, NGM operating temperature and N_2 delivery pressure.

2. Based on the test results gathered for the NSS, an advanced NGM should be designed, developed, fabricated, assembled and tested. The objective of the development activities would be to further reduce NGM weight and power required. A passive thermal design is desired such that the heat generated during N_2H_4 dissociation is sufficient to maintain the NGM at temperature without thermal controls.

3. A preprototype NSS should be designed. This NSS should include an advanced NGM; the mechanical, electromechanical and electrical components; and the N_2H_4 storage and feed mechanism. The NSS should also include a minicomputer-based C/M I with a CRT and a dedicated keyboard. The C/M I must provide automatic mode and mode transition control, automatic self-protection should critical parameters exceed tolerance levels, monitoring of typical subsystem parameters and an interface with ground test instrumentation including data acquisition. The design effort should consider future habitability module requirements and specifications to ensure that the preprototype NSS design is applicable to future (1985-1990) EC/LSS requirements.

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